Applied Energy 204 (2017) 572–581

Contents lists available at ScienceDirect

Applied Energy

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

Multimode power processing interface for fuel cell range extender in battery powered vehicle

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HIGHLIGHTS

- Small-signal analysis of a non-inverting multi-mode buck-boost converter with dual carrier modulator is performed.
- Simple dual-loop controller is derived to assure decent tracking and disturbance rejection capabilities.
- The system is utilized as fuel cell power processing interface in electrical powertrain.
- Simulations and experiments are shown to validate the presented findings.

ARTICLE INFO

Article history:
Received 28 March 2017
Received in revised form 21 June 2017
Accepted 15 July 2017

Keywords:
Non-inverting buck-boost converter
Power control
Fuel cell
Range extender

ABSTRACT

Uninhabited electric vehicle typically utilize batteries as an exclusive power source. In order to remedy the limited energy density and thus operation time of the battery-powered unmanned vehicles, fuel based range extenders are often utilized. The operation strategy for the range extender is to maximize the mission endurance therefore it should operate at minimum specific fuel consumption point. Furthermore, the source and load voltage level may differ, hence non-inverting Buck-Boost converter (NBC) is conjoint them while keeping the desire operation point. This paper proposes a fuel cell (FC) based range extender, interfaced to the main power bus by cascade output power regulation strategy for NBC. The NBC is based on unique modulator that produces switching sequence for both converter legs. The modulator receive single control input from the dual loop regulator, inner inductor current loop and outer output power loop, which is common for energy management strategies of hybrid energy sources. System design commences with regulator design based on small signal analysis of NBC, and then it is shown that the suggested control architecture allows tight output power control throughout the entire operating range despite various plants. Finally a case study is presented, in which the converter operates as power processing interface of a fuel cell, operating as range extender in an all-electrical aircraft. The revealed findings are well-supported by simulation and experimental results.
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1. Introduction

The concept of range extension involves utilizing high-energy sources to enhance vehicle endurance. High theoretical efficiency, zero emissions operation and low thermal and acoustic signatures of FC make them one of the most promising candidates to replace the internal combustion engine (ICE) as the high-energy source in electric vehicle applications. Nevertheless, since the dynamic response of FCs is restricted, hybridizing with a dynamic source is essential [1,2]. In general, instantaneous load power P_L can be decomposed into two components: steady (average) power $P_{l,avg}$ and zero average dynamic power $P_{l,dyn}$. A typical uninhabited aircraft (UA) contains a single energy source (ICE or battery pack), supplying both components of P_L. When quiet and/or emission-free operation is required, electrical propulsion is preferred. Unfortunately, limited energy density of modern batteries restricts operation time of the UA. Moreover, since typical UA mission requires high take-off power, high-energy batteries cannot be used because of the power-energy trade-off. As a solution, splitting the electrical source into an energy unit (FC) and power unit (battery) is proposed in this paper, creating a DC micro-grid shown in Fig. 1. There, the FC is responsible for steady-state operation (cruising)

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http://dx.doi.org/10.1016/j.apenergy.2017.07.043
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Nomenclature

NBC	non-inverting buck-boost converter	v_{BUS}	bus voltage
FC	fuel cell	PI	proportional integral
ICE	internal combustion engine	p_L	load power
Li-Po	lithium polymer	v_S	input source voltage
UA	uninhabited aircraft	i_L	inductor current
PEM	Proton Exchange Membrane	i_{REF}	reference current
MEP	Maximum Efficiency Point	v_O	output source voltage
MSFC	Minimum Specific Fuel Consumption	p_O	output power
MPP	Maximum Power Point	p_{REF}	reference power
PWM	pulse width modulation		
BW	bandwidth		

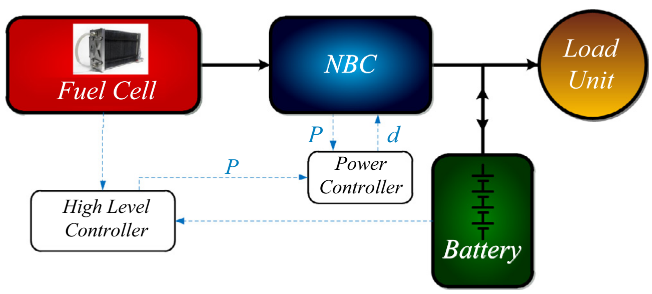

Fig. 1. Case study topology. P^* and P denote reference and actual NBC output power, d symbolizes control input to the converter.

and hence ideally supplies the average power $P_{l,avg}$ (determining the mission length), while the battery is answerable for the transient-state operation (take-off and maneuvering) and therefore supplies the dynamic power $P_{l,dyn}$. Consequently, the range extender is expected to inject a power with slow dynamics into the system in order to enhance the operating range of the UA. Theoretically, this leaves the battery to supply the dynamic component of the load power only.

The progress of the FC technology has recently resulted in releasing a series of commercial devices to the market. Proton Exchange Membrane (PEM) based FC (converting hydrogen to electricity) is probably the most common off the shelf technology. Several companies produce PEM FC stacks at 30 W–5000 W power ratings [3]. A significant barrier for PEM FC widespread use is the use of hydrogen, which is extremely flammable. Another disadvantage is the fact that when stored in a typical high-pressure cylinder (~200 bar), hydrogen represents only 6% of the total weight. One of the solutions for both mentioned problems is a hydrogen generator, which blends borohydride with water to produce hydrogen [4]. The Aeropak by Horizon Fuel Cell Technology is one of the off-the-shelf products, utilizing this method. The unit is capable of supplying up to 200 W continuously, achieving the energy density of circa 700 W h/kg.

It is well known, that FC possesses an optimal operating point, referred to as "Maximum Efficiency Point" (MEP) or the "Minimum Specific Fuel Consumption" (MSFC), where the specific fuel consumption (amount of fuel consumed for producing a unit of electrical energy) is minimal [1]. It should be mentioned that the FC power output at MEP is lower than the device rated power, referred to as "Maximum Power Point" (MPP). In addition, the FC is a soft source [5], possessing nonlinear static I-V characteristics and may be defined either as voltage, current or power source.

Switching power converters are the most common energy processing units for power delivery in modern renewable and alternative energy related applications. Micro-grid is one of the most evolving discipline, formed by distributed energy resources with clearly defined electrical boundaries acting as a single controllable entity with respect to the main grid and can be connected to and disconnect from the grid to enable both grid-connected or island mode operation [6,7]. In DC micro-grids sources, storage and loads are connected by power converters to one or more common DC buses [1]. Three basic conversion topologies (buck, boost and buck boost) are typically achieved by utilizing three basic dedicated circuitries while basic buck-boost converter suffers from relatively low efficiency and polarity inversion. As a remedy, NBC is capable of stepping the output voltage up and down, based on cascaded connection of basic buck and boost stages sharing a common inductor was proposed in [8–10]. The NBC was used in applications such as power factor correction [11], maximum power point tracking in photovoltaic cells [12,13], fuel cell voltage regulation [14–17], battery charging [10,15,18], electrical vehicle [19–23] and micro-grids [24,25]. In all the mentioned applications, DC/DC converter was used to obtain regulated either input or output voltage [26].

During NBC operation, multiple mode transitions occur, resulting in time-varying nonlinear behavior which increases the control challenge. The controller is required to drive both buck and boost legs with different pulse width modulation (PWM) sequences [27]. One of the main drawbacks of proposed methods is the non-smoothness of mode transitions, requiring careful treatment. Recently, a modulator receiving a single control signal from the inner current loop controller and driving both converter legs was proposed in [27]. The NBC with the proposed circuitry was shown to automatically benefit from smooth mode transitions. The feature is particularly important when interfacing a low-dynamics energy source such as fuel cell.

In order to both enhance disturbance rejection and obtain tight current regulation, dual-loop control structures were proposed in [27–30] for NBCs with classical modulators. Inner loop current control for the NBC with the improved modulator was discussed in [27]. It was shown that the small signal representation of the converter is different from the classical one due to the non-similar modulator.

As mentioned above, in most of NBC applications, input or output voltage is the controlled variable. Nevertheless, when operating as power processing interface of a unidirectional energy source, power control rather than voltage control is required in case DC bus voltage forming is carried out by another unit/s. Energy management algorithm is usually executed by a high-level controller, which generates power reference command/s to all the controlled source/storage units. Therefore, small-signal system analysis of the power conversion interface is required with output power playing the role of output loop controlled variable,

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