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Energy efficiency of multiport power converters used in plug-in/V2G fuel cell vehicles

Nicu Bizon *

University of Pitesti, 1 Targu din Vale, Arges, 110040 Pitesti, Romania

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ABSTRACT

In this paper is presented an analysis of energy efficiency for the Multiport Power Converters (MPCs) used in Plug-in Fuel Cell Vehicles (PFCVs). A generic MPC architecture for PFCVs is proposed, which is analyzed for different operating modes of MPC in relation with PFCV operating regimes and the plug-in feature. The basic MPC architecture is described in relation with the PFCV operating regimes. Two MPC architectures are derived from the basic MPC architecture: (1) the MPC1 architecture, which is the MPC architecture without reverse power flow during regenerative braking process, and (2) the MPC2 architecture – MPC architecture without charging mode of Energy Storage System (ESS) from the FC system. Taking in account the imposed window for the ESS state-of-charge, the MPC can be connected to Plug-in Charging Stations (PCS) to exchange power with the Electric Power (EP) system, which will include renewable Distributed Generation (DG) systems. The Energy Management Unit (EMU) of MPC can communicate with the EP system to determine the moments that match the energy demand of plug-in vehicle with the supply availability of the EP system, stabilizing the EP system. The MPC features regarding its energy efficiency were shown by analytical computing performed and appropriate simulations presented in relation with the ESS that can be charged (discharged) from (to) the home/DG/EP system.

1. Introduction

Electric Vehicle (EV) is a technology that promises to drastically reduce emissions associated with road transport. In the last decade the technology has been supported by different manufacturers and specialists as a key element in reducing CO_2 emissions (as well as emissions of pollutants and noise) of cars and light commercial vehicles. But at the same time, EV technology is still far from being projected as necessary, emphasizing too many uncertainties regarding the issues to be addressed, such as [1]:

- The battery technology (energy capacity in relation to vehicle range and road range, fast charging, durability, availability and environmental impacts of used materials).
- Well-to-wheel impacts on emissions.
- Interaction with the DG system.
- Cost of large scale introduction.

On the other hand, battery-powered EVs technology has some advantages over conventional Internal Combustion Engine (ICE) vehicles, such as high-energy efficiency and zero environmental pollution. However, the performance is far less competitive than ICE vehicles, due to the much lower energy density of the batteries than that of gasoline. Consequently, the Hybrid Electric Vehicle (HEV) that uses two power sources has the advantages of both technologies – the ICE and EV technology, and overcome their disadvantages. So, the HEV technology is promoted in meantime by the main companies that design and produce cars. As it is known, HEV combines an ICE with an on-board rechargeable ESS to achieve better fuel economy than a conventional vehicle, without having a road range limitation as an electric vehicle. A number of HEVs are in current production and now are available for purchase, such as the hybrids models from Toyota (Lexus), Honda, Chevrolet, Ford, Mercedes Benz, and so on.

Interaction of vehicle with the DG system is a relatively new concept defined by the plug-in features (referring mainly to the integration of an on-board charger or using of an external charger). Plug-in vehicles can be classified into different categories such as EV, HEV, Plug-in Hybrid Electric Vehicles (PHEV), and Plug-in Fuel Cell Vehicles (PFCV) [2].

Update information about EVs and a concise classification of EVs are given in [3], as below:

- Full Electric Vehicles (FEVs) that have an electric motor and no ICE or Fuel Cell (FC) system.

* Tel.: +40 348 453 201, +40 722 895 624; fax +40 348 453 200.
E-mail addresses: nicubizon@yahoo.com, nicu.bizon@upit.ro

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- PHEVs that have both an ICE and an electric motor, and a battery that can be charged from the renewable PCS/DG system.
- Electric Vehicles with a Range Extender (EREVs) that have one or more electric motors and an ICE or a FCS that can be used to charge the ESS, and thus extend the vehicle's road range. The ESS of an EREV can be charged from renewable PCS/DG system, too.

A FCV is an EV with a FC system operating as range extender. Even if the FCVs are totally different from the conventional ICE powered vehicles and ICE-based hybrid drive trains, however the main car's manufactures already announced their FCVs, with or without plug-in facilities. They have supported ongoing research into the development of FC technology for use in FCVs and other applications. Hydrogen production, storage and distribution are the biggest challenges, so the FCVs still have a long way before entering the market.

The purpose of this paper is to demonstrate that there are many design options for MPC architecture of a PFCV. The typical MPC architecture for a PFCV is presented in Fig. 1, where FC system usually powers (near to its Maximum Power Point (MPP)) the DC bus via a DC-DC power converter named Power Interface 1 (PI 1).

The inverter system is usually of bidirectional type, so the PI 2 must be of bidirectional type, too. The PIs 1&2 could be integrated in one PI of multi-inputs type using different integrated power topologies [4,5]: bi-buck, bi-boost, or hybrid integrated topologies. During the regenerative braking process, the power flows from load to ESS via the inverter diodes and the PI2 operating in buck mode [5]. Because the bidirectional type is more expensive than unidirectional type, some FCVs architectures use the unidirectional boost converter type for PI 2 [4]. Consequently, for charging the ESS used in the MPC architecture based on unidirectional inverter is necessary to use two additionally PIs, which are power converters of DC–DC and AC–DC unidirectional type (named as PI 3 and PI 4, respectively). If the inverter system (PI 5) and the PI 2 are of bidirectional type, then a series connection of these PIs (working in reverse mode during regenerative braking process) could be modeled by the PI 4, too. Consequently, the architecture shown in Fig. 1 is a generic MPC architecture that permits to study the energy efficiency of whole MPC, having as energy sources the FC system and the ESS, and as output(s) the AC electrical machine(s).

The concept of MPC (or Multi-port Power Electronic Interface) is commonly adopted to process the renewable power from multiple sources and loads [6–8], having the following main features: (1) maximum energy harvesting from renewable sources, (2) optimal management of energy from multiple sources, (3) optimal ESS management, and (4) adaptive energy management system for the best performance. The MPC represents a particular case of energy hub concept that is considered as a unit where multiple energy carriers can be converted, conditioned, and stored, representing an interface between different energy sources and loads [9–11].

The MPC creates an interface between loads, renewable sources, and storage elements to efficiently provide and recover power. Consequently, the MPP tracking guarantees optimal energy harvesting from energy sources that have a power characteristic with a maximum at its MPP. The proposed architecture is a flexible MPC topology, generalizing the most used MPC topologies in automotive applications such as the series and parallel MPC topologies, which means the use of an ESS of low voltage (LV) and high voltage (HV) type, respectively [12–14]. In [12] it is shown that this MPP architecture is more efficient than both series and parallel MPC topologies when the ESS is operated to have final State-Of-Charge (SOC) equal with the initial SOC. Here, is analyzed the case when the final ESS SOC is different from the initial SOC. This case may be of interest in operating the PFCV. Also, for the architectures that are derived from the basic MPC proposed, in this paper will be shown that each could work more efficiently under certain

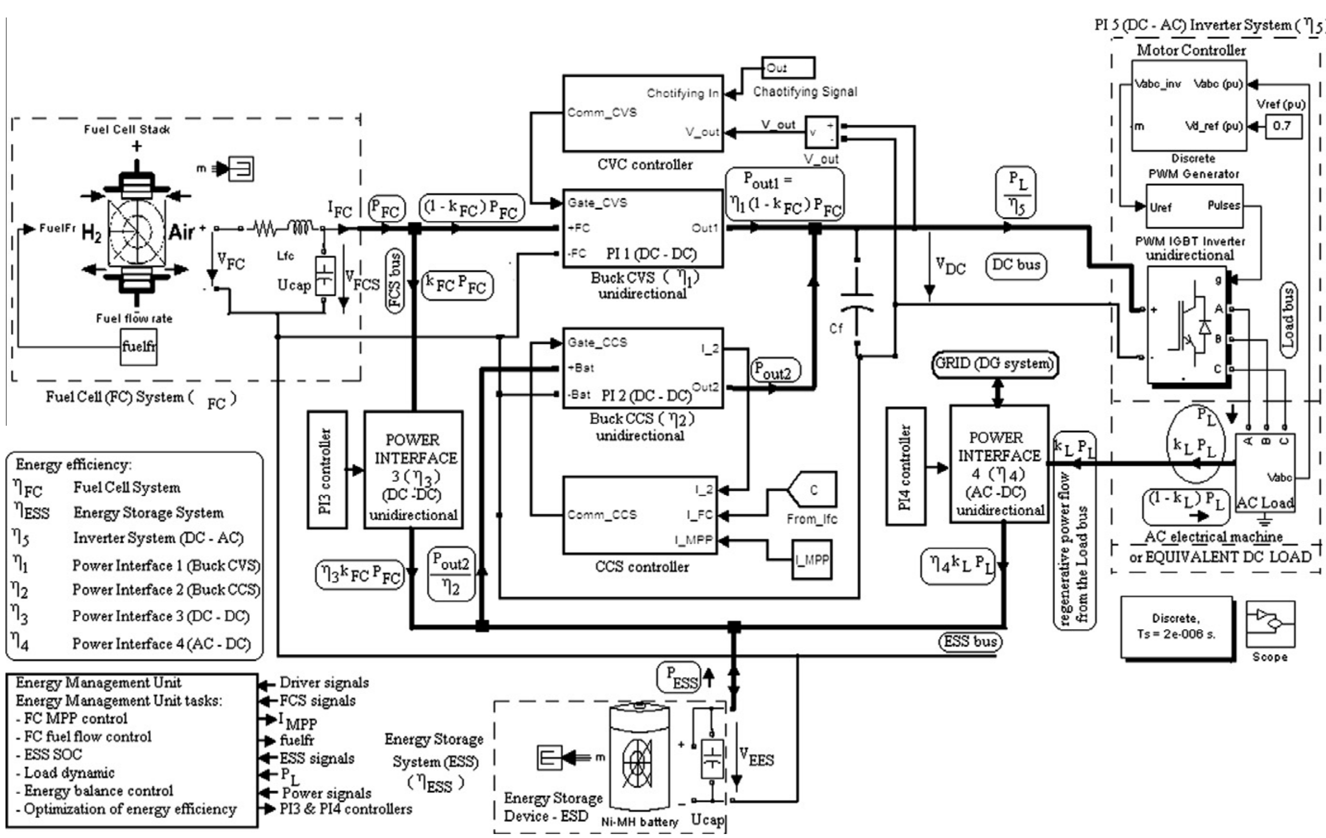

Fig. 1. Plug-in fuel cell vehicle – generic MPC architecture.