Autonomous Hybrid Vehicles

Intelligent Transport Systems and Automotive Technologies

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Chapter

ENERGY EFFICIENCY OF THE HYBRID POWER SOURCE USED IN THE PLUG-IN FUEL CELL VEHICLES

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ABSTRACT

In this chapter a mathematical analysis of the energy efficiency for the series and parallel Multiport Power Converter (MPC) topologies used in the Plug-in Fuel Cell Vehicles (PFCVs) is presented. Besides this study, that is performed and validated in the second part, the first part presents a brief overview over the electric vehicles with a range extender, which also include the electrical motors and inverter systems used, the main parameters of the DC input sources for electrical vehicle, and the usual strategies for the energy management unit. The aim of the analytical study shown in the second part is to provide some general strategies for the energy management unit operating under a wide range of PFCV regimes. The goal is to choose the optimal parameters of the MPC control for an efficient use of the PFCV during each particular drive cycle. In relation with the FC system of PFCV, the Energy Storage System (ESS) can be operated in the following regimes: (1) charge-sustaining, (2) charge-depleting, and (3) charge-increasing.

Considering the imposed window for the ESS state-of-charge, the MPC can be connected to the renewable plug-in charging stations to exchange power with a smart grid, when it is necessary for both. The energy management unit that communicates with the smart grids will establish the moments to match the PFCV power demand with the grid supply availability, stabilizing it. The MPC energy efficiency of the PFCVs is studied when the ESS is charged (discharged) from (to) the smart grid. The comparative results were shown for both PFCV architectures through the analytical calculation performed and the appropriate Matlab/Simulink® simulations presented.

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NOMENCLATURES

RES	Renewable Energy Sources
PV	Photovoltaic panels
WT	Wind Turbines
HT	Hydraulic Turbines
PEMFC	Proton Exchange Membrane Fuel Cell
ESD	Energy Storage Devices
HPS	Hybrid Power Source
HEV	Hybrid Electric Vehicles
FCV	Fuel Cell Vehicles
EGS	Energy Generation Systems
DG	Distributed Generation
UPS	Uninterruptible Power Supplies
EMU	Energy Management Unit
ESS	Energy Storage System
MPPT	Maximum Power Point Tracking
MEP	Maximum Efficiency Point
SOC	State-of-Charge
EV	Electric Vehicle
ICE	Internal Combustion Engine
PCS	Plug-in Charging Stations
PHEV	Plug-in Hybrid Electric Vehicles
PFCV	Plug-in Fuel Cell Vehicles
FEV	Full Electric Vehicle
EREV	Electric Vehicle with a Range Extender
PI	Power Interface
IM	Induction Motor
SRM	Switched Reluctance Motor
PMSM	Permanent Magnet Synchronous Motor
BLDC	Brushless DC motor
PMBLDC	PM Brushless DC
ZSI	Z-Source Inverter
DSP	Digital Signal Processing
CVS	Controlled Voltage Source
CCS	Controlled Current Source
UC	Ultracapacitor
AGM	Absorbed Glass Mat
VRSLAB	Valve Regulated Sealed Lead-Acid Battery
CS	Charge-Sustaining
CD	Charge-Depleting

CI	Charge-Increasing
V2G	Vehicle-to-Grid
MPCs	Series MPC
MPCp	Parallel MPC

1. INTRODUCTION

In the last decade an increased interest in flexible and effective systems of power management, which are able to harvest energy from various sustainable sources of energy, such as the Renewable Energy Sources (RES) (photovoltaic panels - PV, wind turbines - WT, hydraulic turbines - HT etc.) or hydrogen-based energy sources (Proton Exchange Membrane Fuel Cell - PEMFC) appeared.

Using at least one energy source from those mentioned above and Energy Storage Devices (ESD: batteries, ultracapacitors, etc.) combined in a hybrid stack (passive, semi-active or active controlled mode). These merged technologies are used as Hybrid Power Source (HPS) in Hybrid Electric Vehicles (HEVs) and Fuel Cell Vehicles (FCVs) [1], in renewable Energy Generation Systems (EGS) [2], in distributed generation (DG) in smart grids [3], in uninterruptible power supplies (UPS) [4], and so on. Usually, the voltage-current characteristics of the energy sources and storage devices are nonlinear and their voltage levels are different from those of the loads. Consequently, a Multi-Port Converter (MPC) must be used to manage the power flow between the inputs and the outputs (energy sources, storage devices and loads) based on an Energy Management Unit (EMU) [5].

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 Energy Storage System (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]. For example, the MPC interfacing the HEV DC buses must meet the following requirements:

- Electrical isolation between the low voltage (LV) and the high voltage (HV) buses;
- Bidirectional power flow for all input and output ports;
- Continuous supplying of the loads;
- Short response time to load changes;
- High energy efficiency and power density
- Safe start-up without complex circuits.

The MPC creates an interface between the loads, the renewable sources, and the storage devices to efficiently provide and recover the power. Consequently, the Maximum Power Point Tracking (MPPT) control guarantees the optimal energy harvested from the energy sources that have a power characteristic with a maximum at their MPP. Generally, it is better to operate the FC system at the Maximum Efficiency Point (MEP), but MPP can also be used because this is easier to track in comparison with the MEP that is more difficult to be estimated [12]. The generic FCV architecture shown in Figure 1 is based on the flexible MPC topology, generalizing the most used MPC topologies in automotive applications such as the series and parallel MPC topologies. These topologies request the use of the ESS on the LV and HV bus, respectively [13, 14].

In [14, 15] it is shown that a hybrid MPP topology is more efficient than both series and parallel MPC topologies when the ESS is operated to have final State-Of-Charge (SOC) different from the initial SOC. This case may be of interest in operating the PFCV. In this chapter will be shown for basic MPC topologies that each could work more efficiently under certain conditions that will be specified by analytical calculation performed. Consequently, the basic MPC topology helps to boost the energy efficiency performance as well as the flexibility in operating the PFCV to increase the driving range and fuel economy. Also, the mass of the MPC could be reduced by using the modularization and integration techniques for MPCs [6], but this is off the topic of this chapter. Finally, it can be noted that the MPC concept represents both integrated PIs and their appropriate control, and also the fact that they operate efficiently under the energy management strategies implemented in the EMU.

A brief comparison of the energy management approaches applied for the PEMFC systems in the literature is made in [16]. The energy management of multiple sources and loads is a complex and difficult task that needs to be solved by the specialists using different strategies based on (1) intelligent concepts [17, 18], (2) local and global optimization approaches [19, 20], (3) frequency decoupling techniques [21, 22], (4) linear and nonlinear controllers used in multiple control loops [23] etc.

The ECU design took recently a more important and detailed place in literature, especially based on the fuzzy logic and on the nonlinear optimization [16, 24].

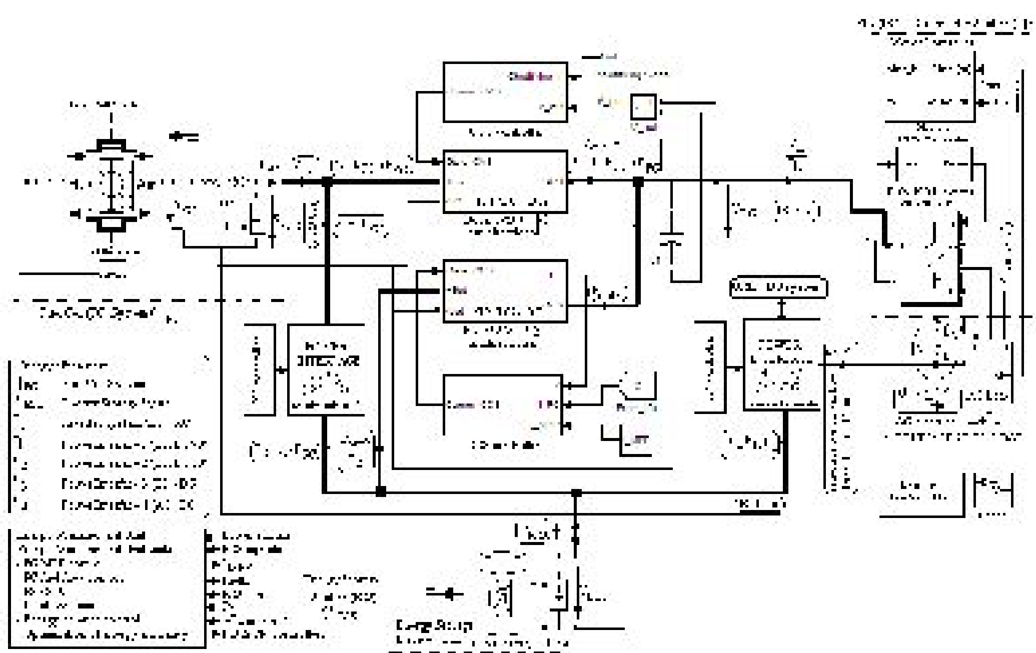


Figure 1. Plug-in Fuel Cell Vehicle - generic MPC topology [14].

This design issue is mainly related to the ECU features of easy adaptation to more complex MPC topologies, computational efficiency, driving rules integration, capacity to modeling uncertainties, etc. [25].

Real-time optimization based on equivalent consumption minimization strategy may be a good choice for the online implementation of the ECU [20]. Finally, all the proposed ECU strategies compare the MPC energy efficiency in term of equivalent hydrogen cost.

In the first part of this chapter (Introduction and the next four sections) the state of art for EVs and HEVs was briefly presented, especially for the FCVs with or without the plug-in feature integrated.

So, these sections shortly present the common electrical motors and inverter systems usually used in automotive applications, the main features of the FC stack and ESS, and the appropriate EMU strategies.

Consequently, a MPC must be used to manage the power flow between the inputs and the outputs (energy sources, storage devices and loads) based on an optimum EMU strategy. Section 6 presents the main MPC topologies proposed in the literature in order to understand the energy efficiency analysis of the MPC performed in the last sections.

The features of the MPCs, which are scalable to meet different power requirements, are presented in relation with the DC input sources in Section 7.

The analysis of the two MPC topologies is presented in the last five sections in term of energy efficiency related to the ESS power flow and the MPC parameters' values.

This part is organized as follows. Sections 8 and 9 present the series and parallel MPC topologies operating in the three operating modes of the ESS. The next two sections (Sections 10 and 11) will compare the energy efficiency for the series and parallel MPC topologies in each ESS operating mode over another.

This analysis is performed to increase the energy efficiency of the whole MPC for series and parallel HPS architectures, which means the use of a LV or HV ESS type, respectively. The analysis is made in term of energy efficiency related to the ESS power flow and MPC parameters. Finally, some conclusions are given related to the PFCV capacity to stabilize the grid by charging/discharging the ESS under EMU control.

2. Plug-In Electric Vehicles with a Range Extender

The Electric Vehicle (EV) is a technology that promises to drastically reduce emissions associated with the 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 [26]:

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

In addition, advantages such as high energy-efficiency and zero environmental pollution will impose the battery-powered EV technology to the internal combustion engine (ICE) vehicles conventional, even if the EV performance is far less competitive than ICE vehicles, due to the much lower energy density of the batteries than that of gasoline.

Consequently, to overcome their disadvantages, the HEV technology was promoted by the main companies that design and produce cars in order to exploit the advantages of the both ICE and EV technologies. HEV combines an ICE with an on-board rechargeable ESS to achieve better performances regarding the fuel economy and road range. The HEVs models are currently produced by Toyota (Lexus), Honda, Chevrolet, Ford, Mercedes Benz etc.

The plug-in concept means the interaction of the vehicle with the DG system through an internal or 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) [27]. EVs classification is given in [28], as below:

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

PHEVs have in addition a charger;

- Electric Vehicles with a Range Extender (EREVs) that have one or more electric motors and an ICE or a FCS, which is used to extend the road range.

A FCV is an EV with a FC system operating as range extender. The car producers announced their FCVs based on ongoing research into the development of the hydrogen technology, even if hydrogen production, storage and distribution are in early stage of implementation. Thus, the FCVs will have a long way before entering the market.

In this chapter will be shown that many design options for the PFCV-MPC topologies are available. The FC system powers the DC bus via a DC-DC power converter (Power Interface 1 - PI1) integrated in the PFCV-MPC topology (see Figure 1), where the inverter system and PI2 are of bidirectional type based on different power converter's topologies [29, 30]: bi-buck, bi-boost, or hybrid integrated topologies.

Note that the power flow during the regenerative braking process is from the load to the ESS via the inverter diodes and PI2 that operate in buck mode [30]. Considering the higher cost of the bidirectional type against the unidirectional type, the bidirectional power flow is split in two unidirectional power flows.

The load is powered via the unidirectional inverter and boost converter - PI2 and the ESS is charged during the brake stage via the unidirectional PI3 and PI4 (of DC-DC and AC-DC type) [29]. PI 4 operates equivalent to the series connection of PI5 and PI2 during the regenerative braking stage.

Thus, the MPC shown in Figure 1 is a generic topology to study MPC energy efficiency, considering the FC system and the ESS as energy sources, and the AC electrical machine(s) as output(s).

3. Electrical Motors and Inverter Systems Used in the Hybrid Electrical Vehicle

Considering the efficiency, cost, size and weight, lifespan and maintainability as performance indicators, the electric traction motors used for HEVs are of following type: the Induction Motor (IM), the Switched Reluctance Motor (SRM), the Permanent Magnet (PM) Synchronous Motor (SM) motor (PMSM), the Brushless DC motor (BLDC), and the new motors such as PM Brushless DC (PMBLDC) [1, 13].

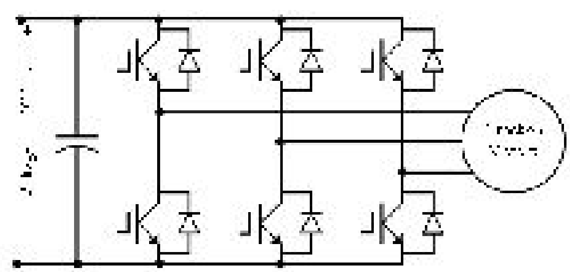
The electric motor operates as a generator to recharge the ESS during the braking stage until to the emergency stopping phase or if the ESS is near to full charge. In a single foot pedal both regenerative braking and mechanical braking modes appear. In the first part of the foot pedal the regenerative braking power flow charge the ESS.

However, the braking requirements for all cars will have to be enhanced in the next decade to meet the new safety stop requirements.

The PM motors have higher efficiency in comparison with the IM, due to the elimination of magnetizing current and copper loss in the rotor. Note that high performance torque control could be obtained using PMBLDC motors, even if these require complex control to operate in both motoring and generating modes [31]. Also note that the IMs and SRMs have the highest reliability, besides other new motors designed for the HEV applications [32].

The electric motor power varies from 10 kW to 100 kW. So inverter system must be designed accordingly. The basic inverter topologies are shown in Figure 2.

The first (a) is a traditional PWM inverter that operates in rectified mode during the regenerative braking. The second (b) is a DC-AC PI (also named inverter) plus a bidirectional DC-DC PI. The third (c) is a Z-Source Inverter (ZSI), with the unidirectional variant shown in plot (d).



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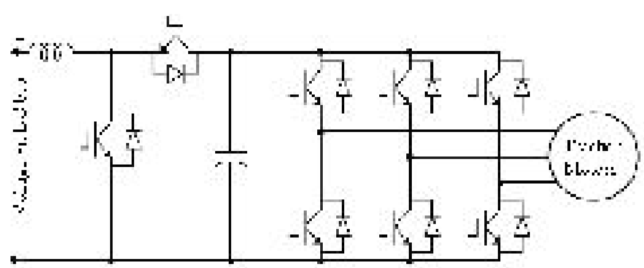
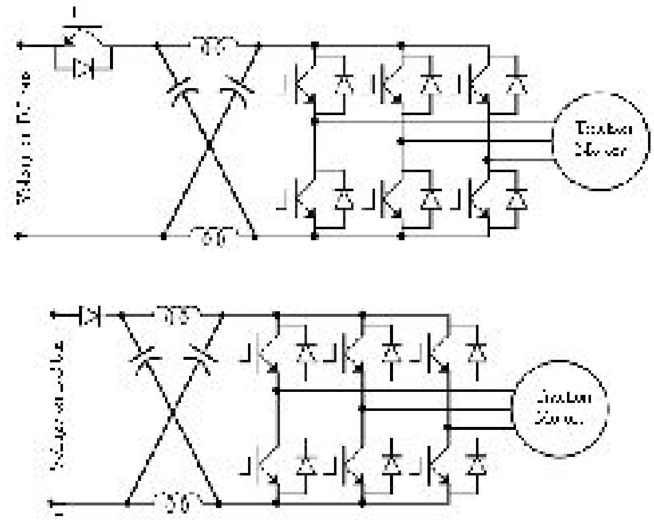


b

Figure 2. (Continued).



c

d

Figure 2. Inverter topologies [14], (a): Traditional PWM inverter, (b): Inverter plus a bidirectional DC-DC PI, (c): Bidirectional Z-source inverter, (d): Unidirectional Z-source inverter.

The bidirectional PIs (Figure 1) will operate in boost and buck mode during the motoring and regenerative braking regime. The voltage on ESS bus usually has a large variation and must be stabilized to the input level required by the inverter [1, 13]. The inverter system will be designed to handle this ESS voltage range at full power load. Note that double of the rated current must be considered at 50% of rated ESS voltage, so the cost of the inverter system will increase. Consequently, the bidirectional PI2 must to be used in order to minimize the inverter stress [33]. The ZSI topology shown in Figure 2c is a PI topology that has interesting features such as buck-boost characteristics and single stage conversion, which can overcome the above mentioned problems [34]. Note that any desired AC output voltage can be obtained, even one greater than the input DC voltage, making the ZSI fed adjustable speed drive systems competitive for the FC automotive applications [35, 36].

A bidirectional ZSI with nine-switches can replace the conventional HEV inverter [37], using the resonant-phase leg inverters instead of hard-switching inverter and new control techniques to increase the energy efficiency and reduce the ripple on the DC bus [38, 39]. Note that the inverter energy efficiency is usually from 0.8 to 0.95.

To better use the PIs must be modular and scalable [6], obtaining a higher production volume and thus a lower cost. Besides this design, the system package, standardization and interoperability among PIs and system are necessary to be considered in MPC design. Such of MPCs will allow designers to use a hub-energy-block approach based on specific functions defined. Thus, the following MPC features should be provided for the design [13]:

› Each MPC should have at least one DC-port and one AC-port;
› All MPC ports must be bidirectional and should be able to operate in a buck or boost mode;
› MPC device’s rating is limited by manufacturer datasheets, so paralleling of MPCs is necessary for high power applications;
› The wiring will be based on the required load power;