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Fuel cell systems reliability and availability enhancement by developing a fast and efficient power switch open-circuit fault detection algorithm in interleaved DC/DC boost converter topologies

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ABSTRACT

Due to the low and unregulated voltage generated by fuel cells, power electronic conditioning systems such as DC/DC converter are required in Fuel Cell Systems (FCS). These FCS are used in different applications with critical loads such as automotive applications, material handling equipment, and backup power. In these applications, it is crucial to guarantee reliability and availability. In FCS, DC/DC converters are one of the most important failure sources. Since the power switches ranked the most delicate components in DC/DC converters, the development of power switch fault detection algorithm is a mandatory step in order to ensure the availability of the system. The purpose of this paper is to propose a fast and original power switch fault detection algorithm based on Park's vectors combined with a Fault-Tolerant Control (FTC) for a 3-leg Interleaved DC/DC Boost Converter (IBC) used in FCS. The developed power switch fault detection and FTC are implemented on a FPGA target, allowing detecting, identifying and handling quickly the faulty power switch. The obtained results from experimental tests confirm the excellent performances of the proposed power switch fault detection algorithm and the FTC.

Introduction

Over the last decades, Fuel Cells (FCs) have known a growing interest from researchers and industrials due to the environmental issues and the depletion of fossil fuels [1]. FCs are electrochemical devices that convert chemical energy directly from an oxygen and hydrogen reaction into electrical energy releasing water and heat. By producing hydrogen from water electrolysis, this allows resulting in zero greenhouse gas

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Nomenclature

Acronyms

AC	Alternating current.
CCM	Continuous Conduction Mode.
DC	Direct current.
DSP	Digital Signal Processor.
FC	Fuel Cell.
FIBC	Floating Interleaved Boost Converter.
FPGA	Field Programmable Gate Array.
FTC	Fault-Tolerant Control.
IBC	Interleaved Boost Converter.
IGBT	Insulated Gate Bipolar Transistor.
JTAG	Joint Test Action Group.
MIBC	Multiphase Interleaved Boost Converter.
OCF	Open Circuit Fault.
PEMFC	Proton Exchange Membrane Fuel Cell.
SCF	Short Circuit Fault.
VHDL	VHSIC Hardware Description Language.

emissions, depending strongly on the source of the electricity used [2,3]. Among all the existing technologies of FCs, Proton Exchange Membrane Fuel Cells (PEMFCs) are being considered for applications that require faster start-up times, compactness, and frequent starts and stops such as automotive applications, material handling equipment and backup power [1,4]. In general, a single cell of PEMFC generates a very low voltage of the order of 0.672 V at rated power [4]. As a result, individual cells are typically combined in series into a FC stack. However, the number of cells combined in series must be limited because stacking more cells in series decreases the reliability of the system [5,6]. For this reason, Fuel Cell Systems (FCs) require power electronic conditioning systems such as DC/DC converters. The low voltage produced by PEMFCs needs to be increased to a regular voltage level. For this purpose, DC/DC boost converters are usually used to step up the PEMFC voltage to the main DC bus voltage. Such DC/DC converter is required not only for the voltage boost but also for the voltage conditioning as the FC stack voltage varies strongly with the load. Besides, DC/DC converters have to meet several requirements for automotive applications, which are [7–9]:

1. Low weight and small volume.
2. High energy efficiency.
3. High power density.
4. Low cost.
5. Low electromagnetic interference.
6. Low input current ripple for both healthy and degraded operating modes to extend the PEMFC lifetime.

In addition, reliability and availability of FCS remain major concern so that they can access to the mass automotive market [10]. Indeed, the presence of failures in PEMFCs and DC/DC converters can lead up to their premature replacements and stop operation [7,11]. In order to guarantee a high level of reliability and availability, FCS have to include fault-tolerant PEMFCs and DC/DC converters. In PEMFCs, the Membrane Electrode Assembly (MEA) can be subjected to different failures: membrane break, internal gas leakage, cell flooding or drying, poisoning of the catalyst areas [12]. Fault-tolerance in PEMFCs has been studied through many papers available in the literature [5,12–24]. The major parts of these papers propose fault-tolerant PEMFCs in order to ensure their availability in case of failures. In Refs. [23], Guilbert et al. have proposed a FTC in order to enhance the performances of the PEMFC in case of drying membrane failures by acting on the control of an Interleaved Boost Converter (IBC) topology. In comparison, Hinaje et al. [24] have developed a membrane failures diagnosis by using the measurements of current and voltage ripples coming from the association of a DC/DC converter and a PEMFC.

By comparison, in DC/DC converters, power switches ranked the most delicate components [25]. Indeed, 31% of reported breakdowns and malfunctions are due to power switches [26]. Due to the importance of power switch failures, many researchers have developed power switch fault detection algorithm in order to enhance the reliability of DC/DC converters [27–36] for photovoltaic and automotive applications. The most common failures in power switches are Open Circuit Faults (OCFs), gating faults, and Short-Circuit Faults (SCFs) [36]. Furthermore, OCFs can be a consequence of SCFs if and only if the fuse melts before the short-circuit damages the system [33,37].

Detection of short-circuit failures is crucial in order to protect the power converter and also PEMFC against high-currents. However, only OCFs are considered in this research work by considering that fuses protect the PEMFC and IBC topology against high currents (Fig. 1). Some authors have proposed the use of dynamic redundancy to make a fault-tolerant DC/DC converter such as DC/DC boost converter [30–33]. It is important to emphasize that the use of dynamic redundancy gets back to increase the cost and the complexity of the converter [38]. For this reason, dynamic redundancy is not fit for automotive applications. According to a thorough review of the power switch fault detection algorithms, % of the reported papers present a power switch fault detection algorithm combined with the use of dynamic redundancy [39].

In order to avoid the use of dynamic redundancy in automotive applications, IBC topology (Fig. 1) is an effective solution. Many papers reported in the literature [7,9,40–43] have emphasized the benefits of this topology compared to other DC/DC converter topologies for fuel cell applications. Indeed, interleaved boost converter topologies present several advantages in terms of compactness, reduced input current ripple, energy efficiency, and reliability in case of power switch faults. However, as it has been emphasized in a previous work [7], operating degraded mode leads up to the drastic increase of FC current ripple, additional hydrogen consumption and finally additional current stresses on magnetic components and power switches. It has been demonstrated in Ref. [7] that the magnetic components can not be saturated as a result of an open-circuit failure by carrying out a thorough analysis on the fuel cell operating range. Furthermore, as highlighted in a previous research work [44], additional current stresses in a 4-leg Floating Interleaved DC/DC Boost Converter (FIBC) are higher than a 3-