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Converters for Optimizimg Power Distribution in Fuel Cell Vehicles

PhD Thesis – Summary

in order to get the scientific title of „Doctor of Philosophy” at
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This thesis is **motivated** by the high impact that power electronics is having on automotive industry, especially in electrical vehicles propulsion. The travel range increase for an electrical vehicle is one of the main goals and together with a smooth, gentle operation and an increased lifetime of the systems, involves a lot of researchers in a continuous and intensive work.

In recent years fuel cells have gained a lot of interest not only for global carbon reduction, but also because hydrogen exhibits desirable properties regarding combustion caloric values, production and transportation costs and cleanliness. They can efficiently convert hydrogen to electrical energy without generating additional pollution. On the other side, dc-dc converters are needed to interconnect the fuel cell and the energy storage in different configurations. The thesis is focused on the use of dc-dc converters for optimizing the powertrain in fuel cell vehicles.

The importance and the actuality of the subject are mainly justified by the progress in the development of hydrogen energy industry in countries like United States, China, South Korea, Japan and Europe. For example, in China, the use of hydrogen energy is mainly focused on the development of fuel cell buses and trucks, while Japan and South Korea are committed to building a hydrogen energy society and hydrogen economy. Thanks to government subsidies, South Korea annual sales of hydrogen vehicles reached 65% of the global sales in 2020, with an impressing rate of 39% year by year. In Europe efforts are made in this direction, through regional projects as well. The PhD candidate was part of such a project funded from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative called “Small 4 Wheel fuel cell passenger vehicle Applications in Regional and Municipal transportation (SWARM)”. The regions that participated in this project were: the British Midlands and Wales (Birmingham, Coventry and Abergavenny), Brussels and the Wallonia region (Liège), and North Western Germany (Wilhelmshaven) and the Cologne area (Frechen).

The scientific objectives to be solved focused on optimizing dc-dc converters in fuel cell electric vehicles.

The research methods adopted are in the traditional approaches in power electronics. They comprise of problem identification, mathematical modelling of the theoretical concept, design, system simulation as a first verification, and finally experimental results as final validation, using a test bench especially built to verify the powertrain systems.

Throughout the thesis the notations and the abbreviations are in perfect agreement to those accepted by the international community, the Anglo-Saxon notations been largely adopted, except for the voltage notation.

The **Introduction** starts by clearly presenting the motivation of the thesis, continuing with the thesis outline, its objectives, and finally specifying the equipment used in the research.

Chapter 1 is dedicated to a presentation of the current state in the field. It is entitled "From Hydrogen Energy to Fuel Cell Electric Vehicle" and it gradually presents the advantages of hydrogen as an energy carrier: environmentally friendly, clean and efficient secondary energy sources, ideal energy interconnection medium, energy storage media that can be applied on a large scale and rich application scenarios. The specific deployments made by the most important countries on the application of hydrogen energy technology in the field of transportation are summarized. Then, according to the type of electrolyte used, a classification of the fuel cells is provided and their operating principle is presented, underlining that the Proton Exchange Membrane Fuel Cell (PEMFC) is better suitable in vehicles because of the low operating temperature, high power density and fast start-up and its characteristics are provided. The chapter then focuses on the powertrain of fuel cell vehicles, comparing the energy flow in a battery electric vehicle and a fuel cell electric vehicle. The author investigated the battery-fuel cell hybrid powertrain identifying two main configurations. In configurations I the dc-dc converter is bidirectional, being inserted between the dc bus and the battery, while in configuration II the dc-dc converter is unidirectional and placed between the fuel cell and the dc bus. In each configuration the required main features of the dc-dc converter are stressed out.

Chapter 2 with the title "Electronic Switch to Control the Powertrain of FCEV" introduces a novel concept for controlling the powertrain in battery fuel hybrid vehicles. Instead of a dc-dc converter an electronic power switch is used to connect the fuel cell and the battery. It consists of six power MOSFETs in parallel. The challenge is that the E-switch has to operate for several seconds in the linear region during the switch-on and switch-off process and this requires the individual MOSEFT currents to be measured and balanced. The characteristics of the linear MOSFET are investigated in detail and the operation with respect to the SOA is studied compared to a standard MOSFET. The operating point trajectory is identified and conclusions are drawn regarding the feasibility of such a switch because of the existence of a certain margin. A step by step switching procedure is proposed. For the current detection circuit closed loop Hall current sensors of LA-55P type are used. For monitoring the relevant parameters of the fuel cell and of the E-switch, to regulate the drain current of the MOSFET by delivering the appropriate control PWM signals and to establish a communication with the fuel stack management system, a STM32F4 MCU microcontroller is chosen. It is shown that the AC component in the D/A conversion is not required and a simple R-C low pass filter is used to remove it. The PI controller design is provided and simulations in MATLAB/Simulink are made in order to verify the theoretical concepts. Finally, the experimental results are presented and the conclusion is that the power losses are divided quite well between the six MOSFETs, which is also confirmed by the temperature profile exposed. The chapter ends with a paragraph revealing the main contributions of the author.

In **Chapter 3**, entitled "DC/DC converter for Powertrain in FCEV", the author proposes a nonisolated multiphase buck converter that is used in configuration II, as it is a unidirectional topology. The analysis starts with the single phase synchronous buck converter, design equations being provided. Emphasis in on input and output capacitors rms currents calculation and the rms inductor current as well and formulae for the reactive elements design are established. The next step is to analyze a multiphase buck converter with interleaved operation and with common input and output capacitors. The individual inductors are designed using an interesting algorithm, based on iterative mathematical equations and also the current ripple in the output and input capacitors are calculated. Comparing the characteristics of the single phase and the N phase multiphase buck converters, it is concluded, as expected, that in the multiphase topology the power of individual modules in 1/N of the total power with reduced device stresses. The input and output ripples are reduced and consequently the input and output capacitors can be reduced allowing for metal film instead of electrolytic capacitors. Also cost and size reduction, together with increased reliability is achieved. Control is an important aspect of the multiphase topology. First the state-space model for the single phase buck with series losses in the reactive elements is classically developed and the transfer functions are calculated. Using this model the transfer functions of the multiphase buck is provided. The Bode plots reveal the important phenomenon that with the number of phases increase, the bandwidth becomes wider and consequently the response becomes faster. Current sharing is also a topic addressed by the author. After briefly presenting the main current sharing methods - master-slave current averaging with dedicated master, average current sharing with democratic control and maximum current sharing with automatic master control – the author's decision goes for current sharing via MCU, in fact a digital implementation of the average current control using a MCU, thus avoiding complex external hardware. The currents in all inductors are measured and the measured values are supplied to a controller that modifies the PWM signals such that the dc components of the inductor currents are equal. The physical implementation and the experimental results for a six phase buck converter are revealing the feasibility of the multiphase converter. A comparison between the unbalanced and balanced situations is made showing the superiority of the latter, by compensating the tolerances of the components and providing equal dc currents. Efficiency versus output power curves are presented showing that excellent efficiencies are achieved especially when slightly stepping down. In the final part of the chapter the control strategy for the single phase dc-dc converter in powertrain is presented. During the start-up process the output current is controlled to rise slowly till the duty cycle is 1 and the fuel cell is directly connected to the dc bus and operates under the passive hybrid condition. The procedure is similar at shutdown. The experimental tests on the test platform developed validated the proposed control strategy. The chapter ends with the conclusions and by mentioning the main contributions of the author.

"Soft-Switching Converters for Fuel Cell Vehicles" is the title of **Chapter 4**, in which two soft-switched topologies, namely a soft-switching multiphase zero-voltage transition pulse-width modulated (ZVT-PWM) synchronous buck converter and a single phase parallel resonant dc-link (PRDCL) buck topology are introduced. It has to be underlined that the chapter could be split into two distinct chapters and the reason for which the author didn't do it is because both topologies belong to the soft-switching category. The soft-switching techniques are first revised, and then the proposed ZVT-PWM converter is presented. The idea starts from a single phase ZVT buck converter reported in the literature that around the classical hard-switching buck makes use of an auxiliary network comprising of a switch, a resonant inductor, a resonant capacitor and a diode. The multiphase topology also starts from the hard-switched *N* phases multiphase converter and uses the same auxiliary resonant circuit consisting of a switch, a resonant inductor and an additional diode. Regarding the resonant capacitor, it is distributed in each phase in parallel to the main switches. Additionally, *N* series switches are inserted between the auxiliary circuit and the legs of the buck converter. It is shown that in steady-state the period is divided into seven operation states. Main waveforms are provided, each state is individually analyzed and its duration is analytically calculated. Briefly, the basic idea to achieve zero-voltage turn on is to connect a capacitor in parallel to the MOSFET and prior to turn on its charge is released to zero in order to achieve zero-voltage turn on. The auxiliary circuit is intended to help in ZVS turn on. The conditions for achieving ZVS are derived and it is interesting that they imply also the number of phases. Design guidelines are also provided. A 2kW two phase synchronous buck converter has been practically implemented to demonstrate de operation, with the STM32 microcontroller for generating the PWM control signals. The oscillograms confirmed the soft-switching process and the efficiency versus load power dependencies were measured both for the ZVT-PWM buck and for the hard-switching topology. The curves showed that for low power levels, less than 400W, the efficiency of the ZVT-PWM converter is not higher than that of the hard-switched counterpart. However, at high power levels the two-phase ZVT-PWM is clearly superior to the hard-switched converter.

In the second part of the chapter a soft-switching multiphase buck converter with parallel resonant DC-link is proposed. The PRDCL employs conventional PWM, with four additional devices: two transistors, an inductor and a diode. The operation of the converter is described in detail and five topological states are identified during one period of operation. For each topological state, denoted with the term "mode", the corresponding circuit is represented and its main equations are derived. First the single phase counterpart was LTSpice simulated and zero-current and zero-voltage switching are confirmed. Then a two-phase topology is simulated. It is identified that a lower conversion ratio compared to the normal multiphase converter is typical to this topology and the phenomenon has the main explanation that the resonant process is strongly influencing the dc output voltage. The static conversion ratio for different duty cycles is theoretically calculated. A two-phase PRDCL prototype was built. The main acquired waveforms are presented together with efficiency measurements and all theoretical considerations are accurately verified. As efficiency is of great concern, below 1300W the converter doesn't bring a better efficiency compared to the hard-switching buck, but above this level, hence at high power levels, its efficiency is higher, with levels around 98.5%. The chapter ends with a summary, conclusions and stressing out the main contributions.

Chapter 5, entitled "Application of Small Fuel Cell Vehicle", presents a test bench for fuel cell powertrain in configuration II. The electric machine with the inverter is emulated by power supplies and electronic loads, allowing for acceleration and deceleration simulation. Because of the master-slave facility, the power supply units can be combined as modules to enlarge the voltage and current range. They can be controlled either manually or by external signals, operating as constant current or constant voltage sources. The HyPN HD8 fuel cell power module is used in the system, operating in the so called "Current Draw Allowed Mode (CDA)". In this mode the output power of the fuel cell is controlled by the bus mode. The oxygen and hydrogen supply system is also described, together with the thermal management system and battery management system. A host computer is used for delivering the control signals to the electronic loads and power supply, thus enabling fully drive cycle simulation. For this purpose the LabVIEW program is used. Main waveforms of a drive cycle can be acquired. The E-switch proposed and presented in Chapter 3 was tested in the test bench. First the tests were performed in switched-on state with variable electronic load. The measured values were recorded during 14 minutes. They were the battery current, the fuel cell current and the maximum allowed current of the fuel cell system. The other set of measurements consisted of the battery voltage and the voltage at the fuel cell. Secondly, the same two sets of measurements were made with the E-switch connecting the fuel cell system and the battery. The recording lasted 20 minutes, starting with the battery state of charge of 15% and being shut down at a 16% state of charge. The measurements proved the feasibility of the "passive hybrid system".

The final chapter, **Chapter 6**, "Conclusions and Contributions", is devoted to the conclusions and underlines the author's main contributions, including the list of publications. In its final part some forecasts and suggestions for possible future research directions are presented.

The results obtained within the thesis were disseminated and validated by publication in international conferences. All the 7 papers published are WoS international conferences indexed, out of which at 4 papers the PhD student is the first author. The papers have 5 citations, without self citations, and the WoS H index of the author is equal to 2.

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