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Control of A high-Performance Z-Source Inverter for Fuel Cell/ Supercapacitor Hybrid Electric Vehicles

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Abstract

This paper presents a supercapacitor (SC) module connected in parallel with fuel cell (FC) stack to supply a high-performance Z-Source Inverter (HP-ZSI) feeding a three phase induction motor for hybrid electric vehicles applications. The supercapacitor is connected between the input diode and the bidirectional switch of the high-performance ZSI topology. The indirect field-oriented control (IFOC) method is used to control an induction motor speed during motoring and regenerative braking operations to produce the modulation index and a dual loop controller is used to control the Z-network capacitor voltage to produce the shoot-through duty ratio. MATLAB simulation results verified the validity of the proposed control strategy during motoring and regenerative braking operations.

Keywords: Z-source Inverter, fuel cell, supercapacitor, indirect field-oriented control.

1. Introduction

Fuel cells (FC) have achieved global attention as an alternative power source for hybrid electric vehicles. A fuel cell vehicle promises zero emission benefits of a battery-powered pure electric vehicle, with the driving range and convenience of a conventional internal combustion engine vehicle [1].

A stand alone FC system integrated into an automotive powertrain is not always sufficient to satisfy the load demands of a vehicle. Although FC systems exhibit good power capability during steady-state operation, the response of fuel cells during transient and instantaneous peak power demands is relatively poor. Besides, if the FC system alone supplies all power demand, it would increase the size and cost of the FC system. Moreover, available FC systems are not capable of recovering the braking energy. Therefore, hybridizing FC system with an energy storage system (ESS) decreases system cost, improves performance and provides regenerative braking energy capturing, thus increases system efficiency and provides energy savings. The ESS is usually a battery module, a supercapacitor module, or a combination of both. However, commercially

available battery systems present some drawbacks, such as low cycle-life, long recharging time and low power densities. Thus, supercapacitors (SC) are being explored as replacements for the batteries in vehicular applications [2, 3].

For the purposes of improving the characteristic and efficiency of hybrid electric vehicles, different hybrid drive train topologies with supercapacitor based energy storage have been analyzed and compared with concern about energy sources control and management in [4]. It concluded that, the direct parallel connection of the fuel cell stack and supercapacitor bank to the DC bus, as shown in Fig. 1, results in the cheapest components solution and the lowest fuel consumption.

The Z-Source Inverter (ZSI) is a single-stage power converter that can perform both inversion and voltage buck/boost without using two separate power conversion stages [5]. There are three different topologies for three phase-two level-voltage type ZSI, they are: the basic ZSI, the bidirectional ZSI and the high performance ZSI. The high performance ZSI can operate at wide load range with small Z-network inductor, eliminate the possibility of the dc link voltage drops, and simplify the Z-network inductor design and system control.

So, the HP-ZSI topology appears to be the most suitable topology for HEV applications [6, 7]. The ZSI can also be applied to FCHEVs with slight modification to include a battery; two configurations have been proposed for FCHEVs as shown in Fig.2 [8, 9]. The first configuration is using a battery connected in parallel with one of the Z-network capacitors, this configuration has some disadvantages such as: a high voltage battery must be used (the battery voltage should equal to the Z-network capacitor voltage) and the dc link voltage is twice the battery voltage during regenerative braking when disconnect the fuel cell. The second configuration is using a battery connected to the motor neutral point, this configuration also has some disadvantages such as: some dc current flows through the traction motor, which increases the motor copper loss, therefore the motor needs to be oversized. In [10], a fuel cell system with the basic single phase ZSI topology and supercapacitors for voltage sag compensation was proposed, the authors proposed six different positions to connect the supercapacitors and they concluded that, the best connection is to connect the supercapacitor between two diodes and overcharging switch, as shown in Fig. 3, however, this configuration doesn't allow bidirectional power flow.

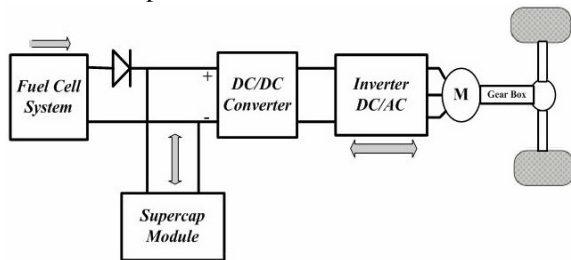


Figure 1: Configuration of FCHEV powertrain with supercapacitor as the energy-storage device

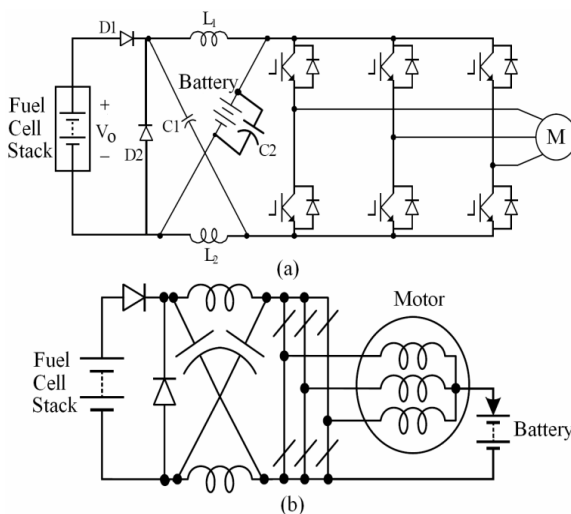


Figure 2: ZSI for FCHEV application: (a) the battery connected in parallel with one of the Z-network capacitors [8], (b) the battery connected to the neutral point of the traction motor [9]

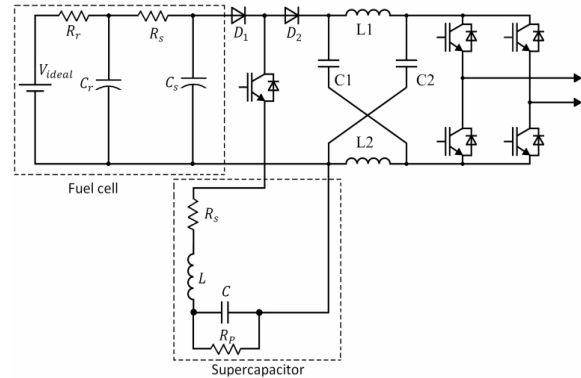


Figure 3: ZSI with supercapacitor connected between two diodes and a switch [10]

In this paper, the fuel cell stack and the supercapacitor module are direct connected in parallel with the HP-ZSI, as shown in Fig. 4. The supercapacitor is connected between the input diode D and the bidirectional switch S_7 . The bidirectional switch S_7 provides a path for the regenerative braking energy to be stored in the supercapacitor during the shoot-through state. The supercapacitor module supplies the transient and instantaneous peak power demands and absorbs the deceleration and regenerative braking energy. Also, a dual loop control capacitor voltage control is used for controlling the shoot-through d_0 duty ratio and the indirect field oriented control (IFOC) strategy is used to control the induction motor speed by controlling the modulation index M .

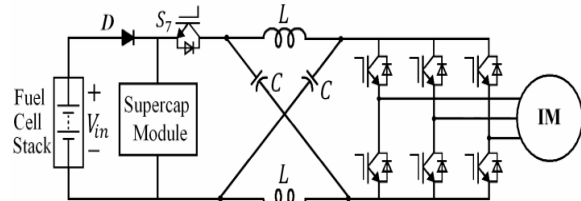


Figure 4: A HP-ZSI with fuel cell and Supercapacitor

2. System Modeling

2.1 Modeling of a PEMFC

A fuel cell is an energy conversion device that converts the chemical energy of a reaction directly into electricity with byproduct of water and heat. The fuel cells are classified according to the choice of electrolyte and fuel into six major different types. The proton exchange membrane (PEM) fuel cell which characterized by low operating temperature, higher power density and quick start up for automotive vehicles [11]. The FC model used in this paper is realized in Simulink/ MATLAB. Then, the model is embedded into the SimPowerSystems of MATLAB as a controlled voltage source. Assuming constant temperature and oxygen concentration, the FC output voltage may be expressed as:

$$G_{vd}(s) = \frac{(-2I_L + I_L)L_L Ls^2 + [(-2I_L + I_L)R_L L + (1 - D_0)(2V_C - V_{in})L + (1 - 2D_0)(2V_C - V_{in})L_L]s + (1 - 2D_0)(2V_C - V_{in})R_L}{L_L L C s^3 + R_L L C s^2 + [2L(1 - D_0)^2 + L_L(2D_0 - 1)^2]s + R_L(2D_0 - 1)^2} \quad (4)$$

$$G_{id}(s) = \frac{(2V_C - V_{in})L_L C s^2 + [R_L C(2V_C - V_{in}) + (1 - 2D_0)(-2I_L + I_L)L_L]s + (1 - D_0)(2V_C - V_{in}) + (1 - 2D_0)(-2I_L + I_L)R_L}{L_L L C s^3 + R_L L C s^2 + [2L(1 - D_0)^2 + L_L(2D_0 - 1)^2]s + R_L(2D_0 - 1)^2} \quad (5)$$

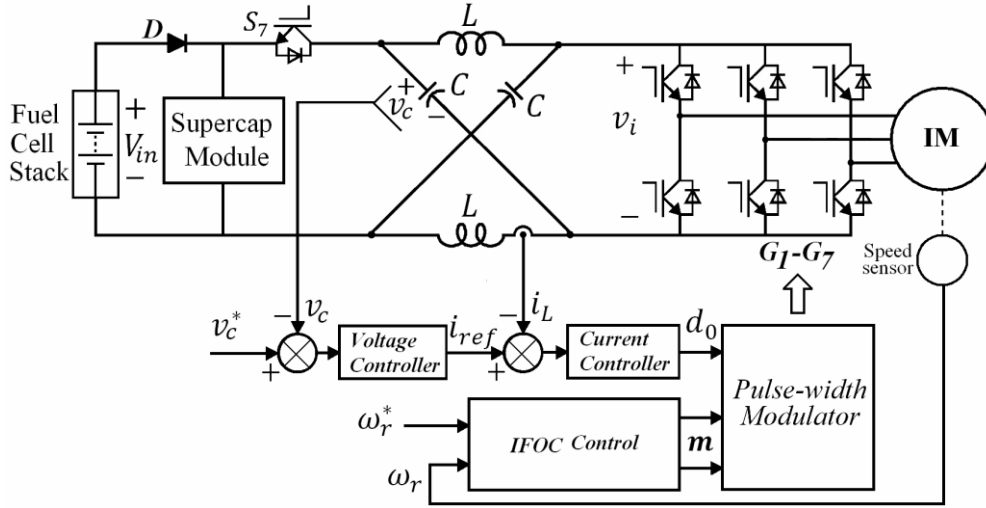


Figure 7: Closed loop speed control of three phase induction motor fed by a high-performance ZSI with fuel cell stack and supercapacitor module

Figure 7 shows the entire closed loop system containing: the fuel cell stack, the supercapacitor module, the HP-ZSI, the Z-network capacitor voltage controllers and the IFOC speed controller, where the capacitor voltage control generates the shoot-through duty ratio d_0 and the IFOC generates the modulation index M according to operating conditions.

The dual loop controller (voltage and current control) is designed to control the average value of the dc link voltage v_i by controlling the capacitor voltage v_c . Equations (4) and (5) gives the required transfer functions for designing the dual-loop control for the HP-ZSI. Figure 8 shows the entire closed loop system containing the outer voltage loop controller, $G_{cv}(s)$, inner current loop controller, $G_{ci}(s)$, modified modulation transfer function, $G_M(s)$, [14], and the shoot-through duty ratio to capacitor voltage $G_{vd}(s)$ and shoot-through duty ratio to inductor current $G_{id}(s)$. The loop gains for inner current loop $T_i(s)$ and outer voltage loop $T_v(s)$ can be expressed as:

$$T_i(s) = G_{ci}(s)G_M(s)G_{id}(s) \quad (6)$$

$$T_v(s) = \frac{G_{cv}(s)G_M(s)G_{vd}(s)}{1 + T_i(s)}$$

For outer voltage and inner current loops, a two poles and one zero controller has been designed to compensate the low-frequency loop gain and improving the phase margin, whose transfer function is given by:

$$G_c(s) = G_{c0} \frac{(1 + \frac{s}{\omega_z})}{s(1 + \frac{s}{\omega_p})} \quad (7)$$

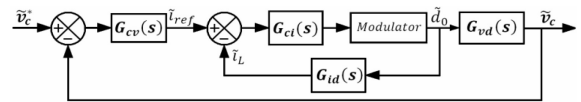


Figure 8: Dual loop capacitor voltage control block diagram of a HP-ZSI

4. Simulation Results

In order to verify the proposed control strategy during motoring and regenerative braking a simulation model is carried out using MATLAB/Simulink software with a 15 kW induction motor. Fig. 9 show the motor response during motoring, regenerative braking operation modes: acceleration mode with rated load torque during the time interval 0-0.2 sec, steady state operation mode with rated load torque and rated speed during the time interval 0.2-0.5 sec, overloaded transient mode with 1.2 the rated load torque and rated speed during the time interval 0.5-0.8 sec, deceleration transient mode from rated speed to half the rated speed with rated load torque during time interval 0.8-1 sec, light load transient mode with half the rated load torque and half the rated speed during the time interval 1-1.2 sec, regenerative braking mode during the time interval 1.2-1.4 sec and standstill mode during the

time interval 1.4-1.45 sec. Fig. 10 shows the reference and actual the Z-network capacitor voltage, where the capacitor voltage is controlled to be 653 V, the shoot-through duty ratio which is generated from capacitor voltage control, the modulating signals which is generated from the IFOC control and the reference and actual Z-network inductor current. Fig. 11 shows the fuel cell stack and the supercapacitor module voltages,

currents and SOC of the supercapacitor module during the above mentioned operations modes. Fig. 12 shows the fuel cell stack, the supercapacitor module and motor electric powers during the above mentioned operations modes, the fuel cell stack delivers the rated system power while the supercapacitor module delivers the transient and instantaneous peak power demands and absorbs the deceleration and regenerative braking energy.

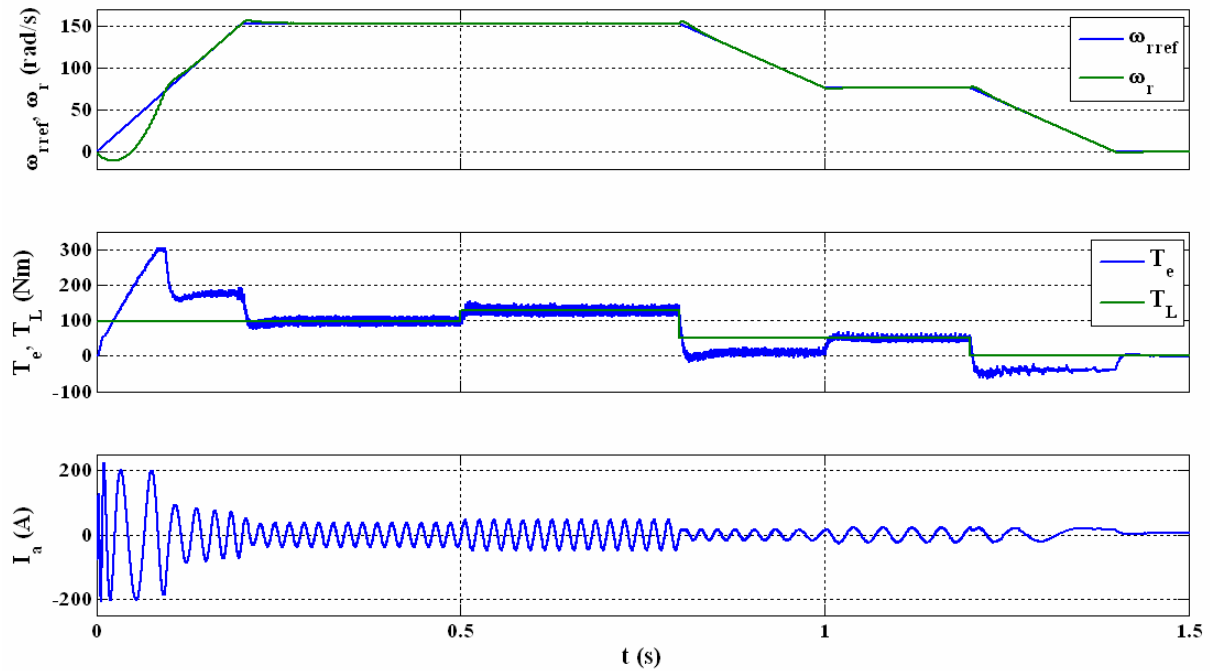


Figure 9: Motor response during motoring and regenerative braking operation modes

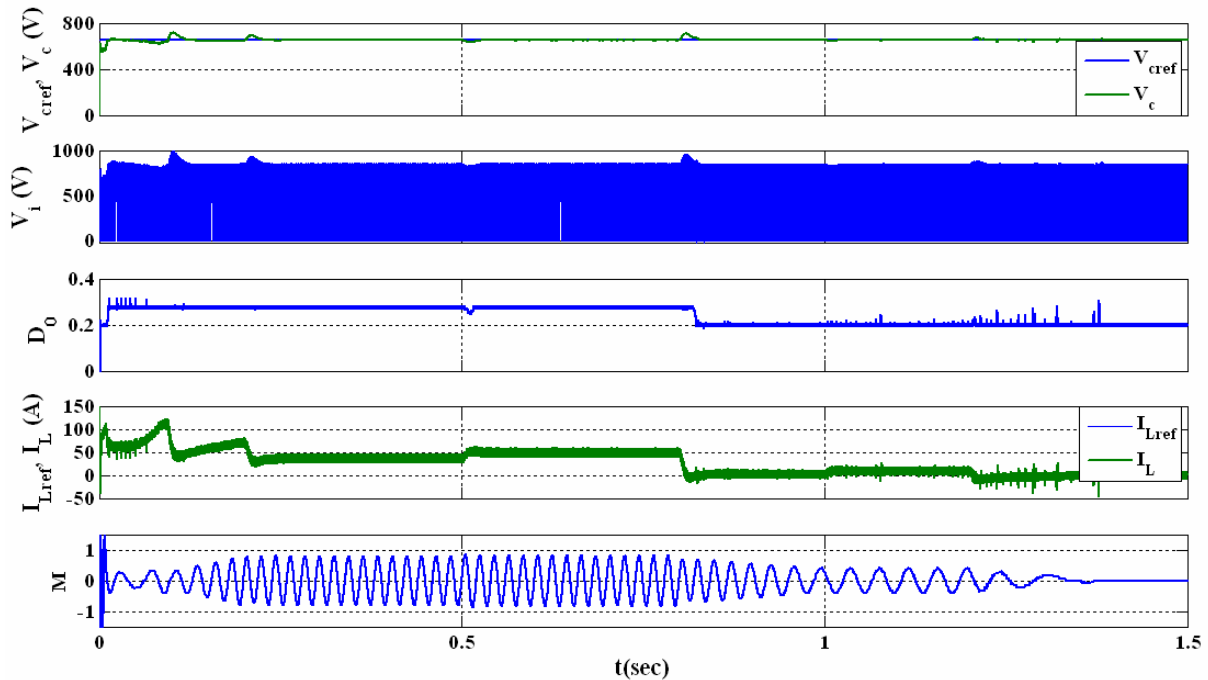


Figure 10: High-performance ZSI response during motoring and regenerative braking operation modes

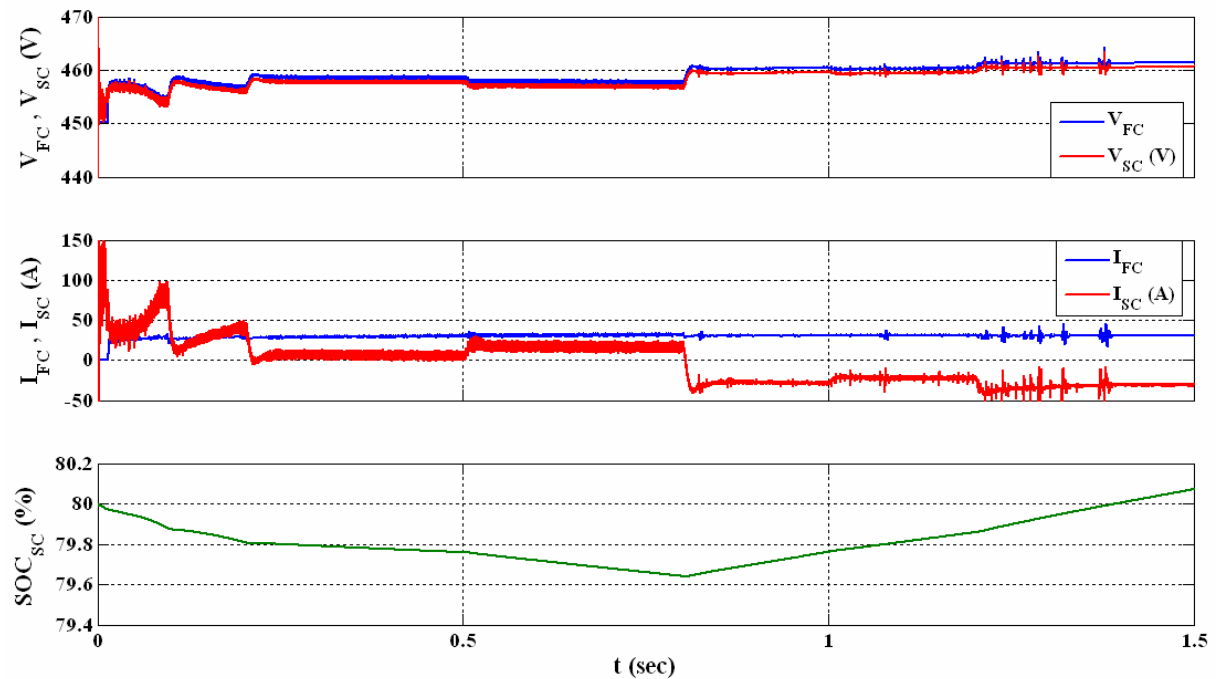


Figure 11: Fuel cell and supercapacitor voltage, current and supercapacitor state of charge during motoring and regenerative braking operation modes

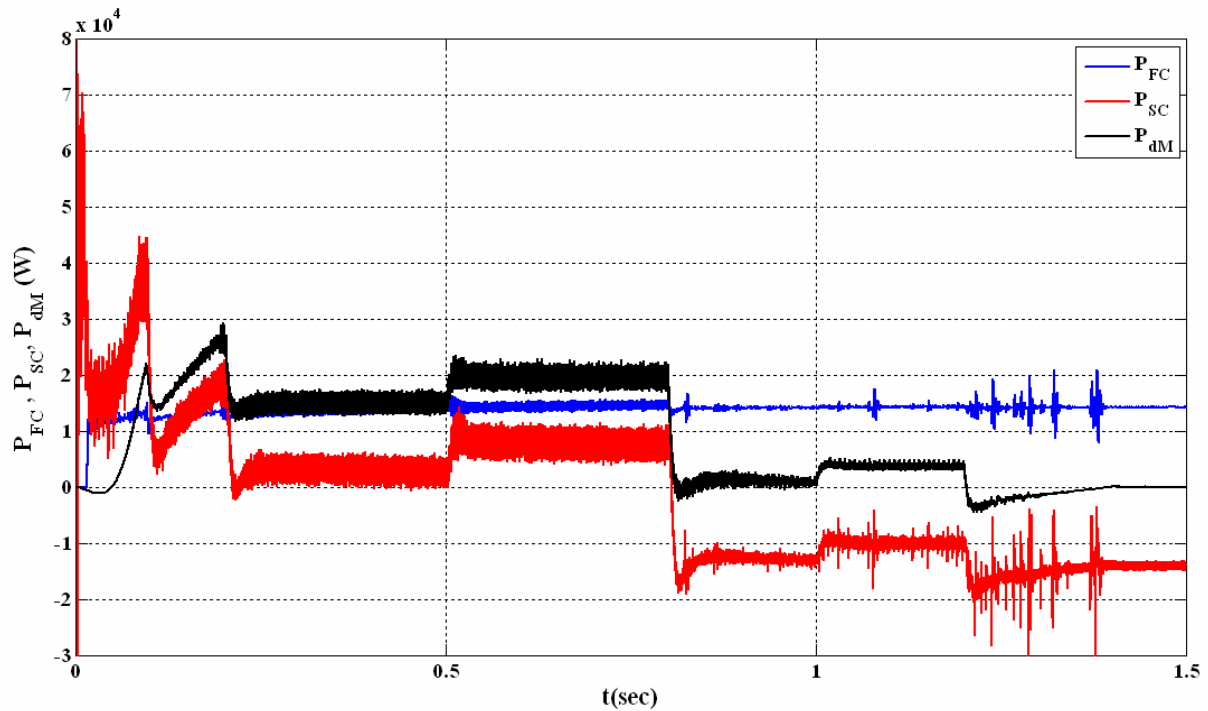


Figure 12: Motor developed power, fuel cell output power and supercapacitor power

5. Conclusions

This paper has presented a FCHEV system supplied by a fuel cell stack and a supercapacitor module using the high-performance Z-source inverter. The fuel cell and the supercapacitor are directly

connected in parallel. The supercapacitor module delivers the transient and instantaneous peak power demands and absorbs the deceleration and regenerative braking energies while the fuel cell stack delivers the system mean power. MATLAB simulation results verified the validity of the proposed system configuration.

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Appendix: System Parameters

Parameter	Value
PEM FC parameters	
Standard no load voltage, E_0	0.95 V
No. of series FC in stack, N_{fcs}	525
No. of parallel stacks, N_{fcp}	17
Supercapacitor (BCAP3000 P270) parameters per cell	
Capacitance (-0% / +12%), C_{SC}	3000 F
DC equivalent series resistance, R_{Ssc}	0.29 m Ω
Leakage current, i_{Rpsc}	5.2 mA
No. of series SC, N_{SCS}	525
No. of SC string parallel, N_{sep}	17
High performance ZSI parameters	
Inductance, L	500 μ H
Capacitance, C	500 μ F
Switching frequency, F_s	10 kHz
Induction Motor Parameters	
Output power	15 kW
RMS line voltage	400 V
Input frequency	50 Hz
No. of poles	4
Stator resistance, R_s	0.2205 Ω
Rotor resistance, R_r	0.2147 Ω
Stator inductance, L_{ls}	0.991 mH
Rotor inductance, L_{lr}	0.991 mH
Mutual inductance, L_m	64.19 mH
Inertia, J	0.102 kg.m ²
Fraction factor, F	0.009541 N.m.s



Dr. Omar Ellabban was born in Egypt in 1975. He received the B.Sc. from Helwan University, Egypt in 1998 and the M.Sc. degree from Cairo University, Egypt in 2005, both in Electric Power and Machines Engineering, and the Ph.D. degree in Electrical Engineering from Vrije Universiteit Brussel, Belgium in May 2011 with the greatest distinction. In May 2011, he joined the R and D department at Punch Powertrain, Sint-Truiden, Belgium, where he and his team develop a next generation, highly performing hybrid Powertrain. His research interests include motor drives, artificial intelligent, power electronics converters design, modeling

and control, electric and hybrid electric vehicles control, DSP-based system control and switched reluctance motor control for automotive applications. He is a member at the IEEE, JPE and EPE journals.



Prof. Joeri Van Mierlo obtained his Ph.D. in electromechanical Engineering Sciences from the Vrije Universiteit Brussel in 2000. He is now a full-time professor at this university, where he leads the MOBI - Mobility and automotive technology research group. Currently his research is devoted to the development of hybrid propulsion (converters, supercaps, energymanagement, etc.) systems as well as to the environmental comparison of vehicles with different kind of drive trains and fuels (LCA, WTW). He is the author of more than 100 scientific publications. Prof. Van Mierlo chairs the EPE chapter "Hybrid and electric vehicles"

(www.epe-association.org), is the secretary of the board of the Belgian section of AVERE (ASBE) and is board member of AVERE. He is co-editor of the Journal of Asian Electric Vehicles. He is an active member of EARPA-the association of automotive R&D organizations. Furthermore he is member of Flanders Drive and of VSWB – Flemish Cooperative on hydrogen and Fuels Cells. Prof. Van Mierlo is Chairman of the International Program Committee of the International Electric, hybrid and fuel cell symposium (EVS24).



Prof. Philippe Lataire received the degree of electromechanical engineer in 1975 and the Ph.D. degree in 1982, both from the Vrije Universiteit Brussel (VUB), Brussels, Belgium. He is presently full time professor at the VUB. The prime factors of his research are in the field of electric drives, power electronics and control.