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## A review and design of power electronics converters for fuel cell hybrid system applications

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### Abstract

This paper presents an overview of most promising power electronics topologies for a fuel cell hybrid power conversion system which can be utilized in many applications such as hybrid electrical vehicles (HEV), distributed generations (DG) and uninterruptible-power-supply (UPS) systems. Then, a multiple-input power conversion system including a decoupled dual-input converter and a three-phase neutral-point-clamped (NPC) inverter is proposed. The system can operate in both stand-alone and grid-connected modes. Simulation and experimental results are provided to show the feasibility of the proposed system and the effectiveness of the control methods.

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Keywords: Fuel cells, electrolysis cell, super-capacitors, converter, inverter, control.

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### 1. Introduction

Sustainable energy is the main driving force for all renewable energy sources applications. Due their nature, energy supply from renewable energy sources is fluctuating depending on the availability of the energy source. Availability of the energy sources is mostly unpredictable (e.g. wind energy, solar energy, etc.) therefore, it is essential to have other energy sources that are more predictable to guarantee energy availability during periods of low energy supply from renewable sources. During period of energy surplus it is advantageous to store energy and make it available during the periods of low energy production and high energy demand. An efficient and high density way of storing energy is to produce fuel to accumulate the energy surplus.

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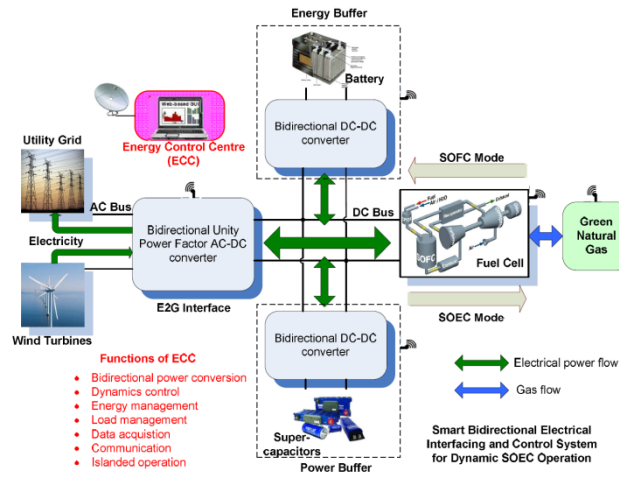


Fig. 1. Block diagram of a fuel cell battery and super-capacitor powered line-interactive renewable generation system.

According to the energy strategy by the Danish government “A visionary Danish energy policy” published on January 2007, the goal is that wind energy should contribute for 50% of the national electricity consumption by 2025 [1]. Large scale integration of wind power and other renewable energy sources will require the development of a suitable grid infrastructure for handling the variability of the generation and load conditions. During periods of high wind the energy surplus from the wind parks is required to be stored or redirected towards other loads in order to avoid wasting precious energy. Large scale integration of solid oxide electrolysis cells (SOECs) and solid oxide fuel cells (SOFCs) based systems represent an attractive solution for handling energy surplus and pitfalls.

SOEC and SOFC operate at high temperatures nearly  $\sim 1000^{\circ}\text{C}$ , compared to other fuel cell technologies (e.g. proton exchange membrane fuel cells, PEM FCs) SOFCs are made of hard solid materials which allow the cell to have different shape and not being limited to a flat plane structure. One of the main advantages of operating at such high temperatures is that there is no need for precious-metal catalyst reducing the costs. Moreover the SO cells can run on a variety of fuels including hydrocarbons; a major advantage is that pure hydrogen is not required however, since the main reactions involved require hydrogen, the fuel must contain hydrogen atoms.

Fuel cells can be operated in reversed mode with reduced efficiency these are known as regenerative fuel cells, the main drawback of this reversibility comes from the low efficiency. This is the main reason why SOFC and SOEC systems for generating and storing energy are mostly based on independent fuel cell and electrolyser [2]. One of the main drawbacks of operating at such high temperature is the long thermal ramp-up required for the cell to avoid damage (due to thermal strains) to the cells.

In newly developments SOEC/SOFC have been allowed to operate at more manageable temperatures ( $< \sim 800^{\circ}\text{C}$ ) allowing using common metallic materials (such as stainless steel) allowing reducing manufacturing cost and increasing reliability of the cell stacks. Operating at high temperatures allows SOEC/SOFC to have very high efficiency [3-4]; for this reason SOEC/SOFC systems are becoming more and more interesting as energy storage and energy source.

Power electronics converters as the interfacing circuits between renewable energy sources, storage elements, utility grid and customers have been more and more and more important for power control, energy saving and system reliability. Integration of power electronic converters as interface for fuel cell (FC) and electrolyser cell (EC) based systems with the grid introduces new challenging issues related to the slow cell dynamics and transient response, therefore, hybrid generation systems are required for

obtaining fast transient response. Additional energy storage elements, such as battery and super capacitor banks, are expected to be a core element for increasing the system dynamic performance. Efficient energy management and control of the system power flows in the various system components is a key point for system performance. The highest reported efficiency for a fuel cell converter is up to ~98% [5] however, no previous research has been found on bi-directional FC/EC applications. In such applications where a wide input voltage range and high current is required, very high efficiency dc-dc conversion remains a challenge [6] and where novel power semiconductor devices based in silicon carbide (SiC) and gallium nitride (GaN), and advanced magnetic components based on new integration methods and magnetic material could provide a significant difference.

Hereby, a diagram block to demonstrate the hybrid generation system based on fuel cell, super capacitor and battery system is presented in Fig. 1.

## 2. Power Electronics Converters for Fuel Cell Hybrid Energy Systems

According to the characteristics of the distributed generation systems based on the fuel cells, interface converters are necessary to boost the low variable voltage from the fuel cells and other auxiliary power sources (APS) such as batteries and super-capacitors, in order to provide the high quality, regulated dc voltage to the cascaded inverter for grid-connecting purposes. Hence, a large number of alternative converter topologies and implementations for low voltage high power applications have been proposed [5], [7]-[8].

### 2.1. Dc-Dc converters

Basically, dc-dc converters can be divided into two categories depending on using the galvanic insulation or not: non-isolated converter or isolated converter. As to the non-isolated converters, normally, boost-type converters are favourable to fuel cell application [9]. These topologies are simple, but they require a bulky input inductor to limit the current ripple in the components, especially with high voltage gains are required. To minimize the input inductor size and the current ripple, as well as to reduce the switch current stress, the converter can be designed with multiple legs interleaving each other by means of the input coupling inductors, and high efficiency can be obtained. For isolated dc-dc converters, in [5], the low voltage high power isolated converters have been overviewed and compared very well. The high efficiency full-bridge boost type fuel cell converter without any auxiliary snubber circuit is designed in [10]. Moreover, a novel parallel method is proposed in [11] to increase the power level to 10 kW. Summarily, as with typical designs, tradeoffs exist in choosing the optimum dc-dc converter, so the designers must establish the exact requirements of the fuel cell system in question to determine the most advantageous design.

As for the interfacing circuits of APS, generally, bidirectional dc-dc converters are needed. Theoretically, all the isolated unidirectional dc-dc converters overviewed in [5] and [7] can achieve bidirectional power delivering ability, through changing the diode-rectifiers to synchronized rectifiers which are based on gate-controlled semiconductors, such as MOSFETs or IGBTs.

### 2.2. Hybrid dc-dc conversion systems

The block diagrams of the widely utilized dc-dc hybrid systems with FCs and APS are summarized in Fig. 2 (a) and (e) [12]. In Fig. 2 (a) and (b), the DC bus is fixed by the fuel cell or by the APS [13]. In this case, the main advantage is related with the fact that the current flows through APSs only during the transients, enlarging the lifetime of the APS. The critical disadvantage is that the usual dc bus conditions

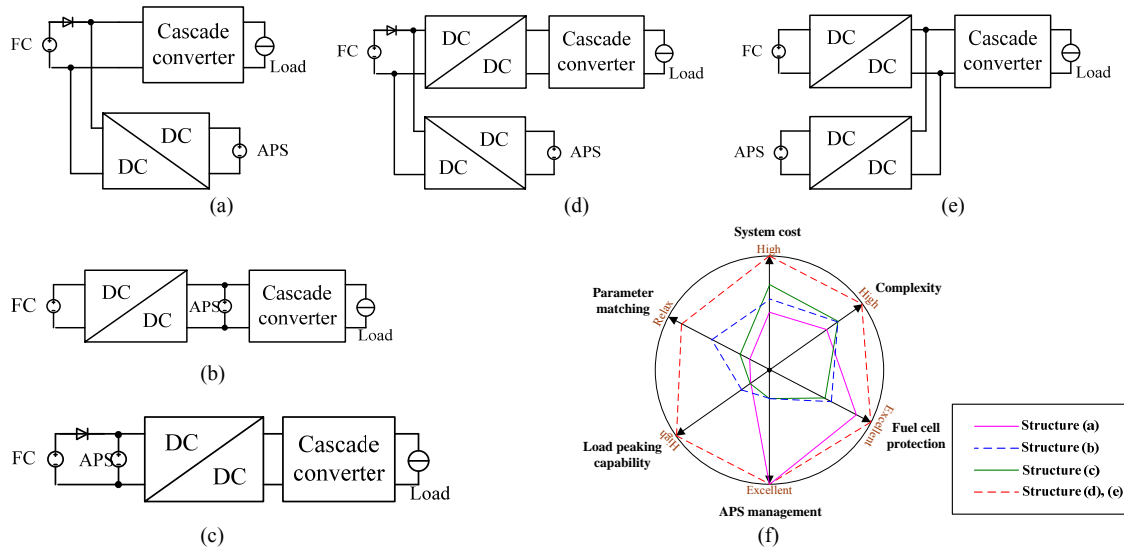


Fig. 2. Various converter connections and comparison.

impose that the DC voltage cannot vary strongly. In Fig. 2 (c), only one power converter is used. The main characteristic of this direct connection is that both elements, the fuel cell and the APS, share the same voltage value. This will reduce the weight and will increase the reliability of the system. But it is difficult to control the fuel cell current flexibly [14]. Fig. 2 (d) and (e) show the block diagrams of the two voltage source power conversion system with two individual dc-dc converters, and hereby the two input power sources are decoupled completely. While, obviously, the cost and complexity of the whole system are increased [15].

Hence, in terms of system cost, complexity, fuel cell protection, super-capacitor management, load peaking capability and parameter matching, the different structures analyzed above are compared in the spider plot as shown in Fig. 2 (f).

In order to simplify the hybrid power conversion system and reduce the system cost, the multiple-input dc-dc converters can be used. The input voltage sources or current sources (voltage source cascaded with large inductance) can be connected either in series or in parallel for the dc-dc converters to transfer the desired power to the load. Furthermore, some parts of the dc-dc converter (such as filter or rectifier) can be shared by different input sources, so it has the potential to achieve higher power density [16], [17].

### 2.3. DC-AC inverters

The DC/AC converter technology is mature and uses mainly the hard-switching voltage source inverter (VSI), with single-phase, dual-phase or three-phase output, controlled by means of sinusoidal pulse-width-modulation (SPWM) or space vector PWM (SVPWM) [18]. Multilevel voltage-source inverters [19] provide a cost effective solution in the medium voltage energy management market. Nowadays, there exist three commercial topologies of multilevel voltage-source inverters: neutral point clamped (NPC), cascaded H-bridge (CHB), and flying capacitors (FCs). Among the high-power converters, the NPC inverter introduced 25 years ago is the most widely used in all types of industrial applications, such as wind power generation, UPS and so on, in the medium and high voltage range.

### 3. Proposed topology and System Design

The authors and other researchers from the Electronics Group, Technical University of Denmark (DTU), have given many contributions on analysis and design of the fuel cell converters. Based on our research results in this topic, a dual-input two-stage power conversion system, including DC-DC and DC-AC is proposed, analyzed and verified in this paper.

#### 3.1. The proposed hybrid power conversion system

The topology of the proposed fuel cell hybrid power conversion system is shown in Fig. 3. A fuel cell is used as the primary source and an APS (supercapacitor or battery) is employed as the transient energy storage. The dual-input dc-dc converter interfaces the fuel cell and the APS to the three-phase NPC inverter and manages the power flow in the system. The inverter output can be connected to the grid or the local loads depending on the grid condition.

Unlike conventional power converters, this new dc-dc stage for a fuel-cell power conditioning system has two power inputs. In this paper, the dual-input isolated boost converter [20] was chosen. The converter topology consists of four individual and uniform transformers and four bridges. The topology is bidirectional due to the active rectifier bridge on the secondary side. In addition to galvanic isolation, this converter can easily match the different voltage levels at the ports. Moreover, the two input ports are decoupled completely by the phase-shift PWM modulation strategy. Based on the modeling of the proposed dc converter, the control scheme can be designed for the dc-dc stage which aims to simultaneously regulate the dc-link voltage and the fuel-cell power with two bridge duty cycles as control variables. The APS sinks/sources the power difference between the inverter and the fuel cell to keep the power of fuel cell constant and match the variations of the power drawn by the inverter [21].

A three-phase voltage source NPC inverter is used for dc-ac power conversion and grid interfacing. The main function of the inverter is to maintain a regulated output voltage when operating in stand-alone mode, and when operating in grid-connected mode, to inject an optional real power as well as reactive and harmonic current into the grid. Because of the boost function in the dc-dc stage, low-voltage fuel cell and energy-storage devices as APS can be utilized in the whole system. A new SPWM modulation strategy based on the circuit-level decoupling algorithm is employed in the NPC inverter. This modulation scheme can not only simplify the closed-loop controller design but also reduce the switching losses [22].

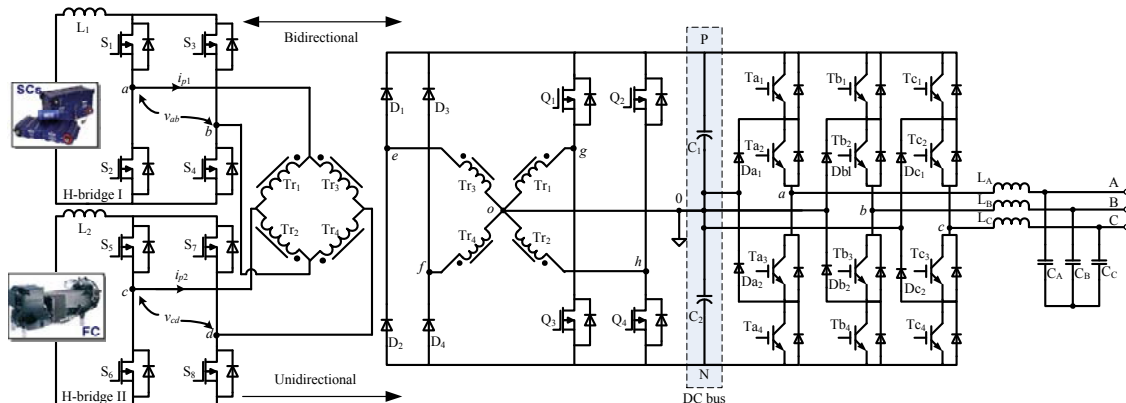


Fig. 3. Proposed DC-DC-DC-AC dual input power conversion system.

### 3.2. Simulation analysis and experimental results

The proposed topology is simulated by Simulink/PLECS where a supercapacitor (SC) bank is used as the APS, and simulation parameters are list in Table 1. Fig. 4 shows relevant waveforms in different operating conditions. During T1, the fuel cells are in warm-up stage and have no output power, so the load is fully powered by the SC bank. The fuel cells start to provide the power and recharge SC bank in T2 in which the bidirectionality of the proposed converter structure can be shown clearly. During T3, the output power of fuel cells is constant and the voltage of SC bank is increasing slowly. The load response of the system is presented in the subinterval of T4 and the transient power is fully taken over by the SC bank rather than the fuel cells.

In order to verify the theoretical analysis, a laboratory prototype of the proposed topology is implemented and tested. The specifications and component details of the tested prototype are given in Table 2.

Table 1. Parameters in the simulation

Name of the Parameters	Value
Fuel cell voltage	50 V DC
SC bank voltage	100 V DC
Dc-link voltage	400 V DC
Output ac voltage	120 VAC
Output power	1000 W

Table 2. Specifications and component details of the tested prototype

Rated input voltage, V1 and V2	30 – 60 VDC
Rated output voltage, Vo	400 VDC
Rated output power, Po	2 kW
Switching frequency of dc-dc converter	50 kHz
Boost inductors, $L_1$ and $L_2$	22 $\mu$ H, N87 ferrite core, copper foil winding
Dc-link film capacitor	6.8 $\mu$ F/250V Film Cap: 4 in parallel
Dc-link electrolytic capacitor	2820 $\mu$ F
MOSFETs $S_1$ - $S_8$	IRFP4568, 150V/171A
Diodes $D_1$ - $D_4$	HFA15TB60, 600V/15A
Ac output filters	$L_A=L_B=L_C=120 \mu$ H, $C_A=C_B=C_C=40 \mu$ F
Switching frequency of NPC inverter	20 kHz
IGBT Ta1-Tc4	600 V/40 A

Fig. 5(a) shows the experimental waveforms of the voltages  $v_{ab-DC}$  and  $v_{cd-DC}$  as well as the currents  $i_{p1}$  and  $i_{p2}$  on the primary side of the dc-dc stage, as denoted in Fig. 3, under the dual-input mode with input voltages of 50 V and 30 V. Fig. 5(b) shows the output voltage response to transients of the two input currents. A small super-capacitor bank (60V/14.6F) is used as input source  $V_{g2}$  and then the experimental waveforms can be obtained and present in Fig. 5(c). At  $t_0$ , the converter starts and  $i_{ref1}$  is 0, which is to simulate the warm-up stage of the primary power source  $V_{g1}$ , so converter operates under single-input

mode. The required load power is provided by super-capacitor bank and output voltage keeps constant; after  $t_1$ ,  $i_{refl}$  is given according to voltage of  $V_{g1}$  and the required output power, and thereby  $i_{g2}$  starts to reduce until it reaches zero at  $t_2$ .

Fig. 5(d)-(f) show the experimental waveforms obtained on the NPC inverter with the circuit-level decoupling SPWM modulation strategy.

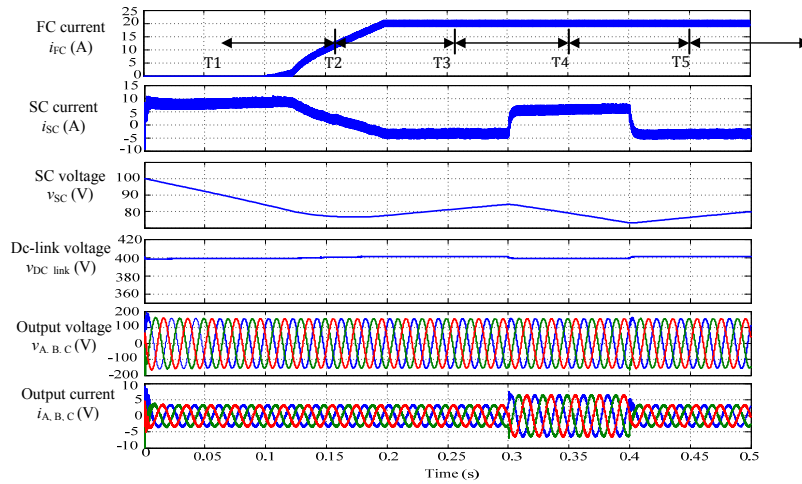
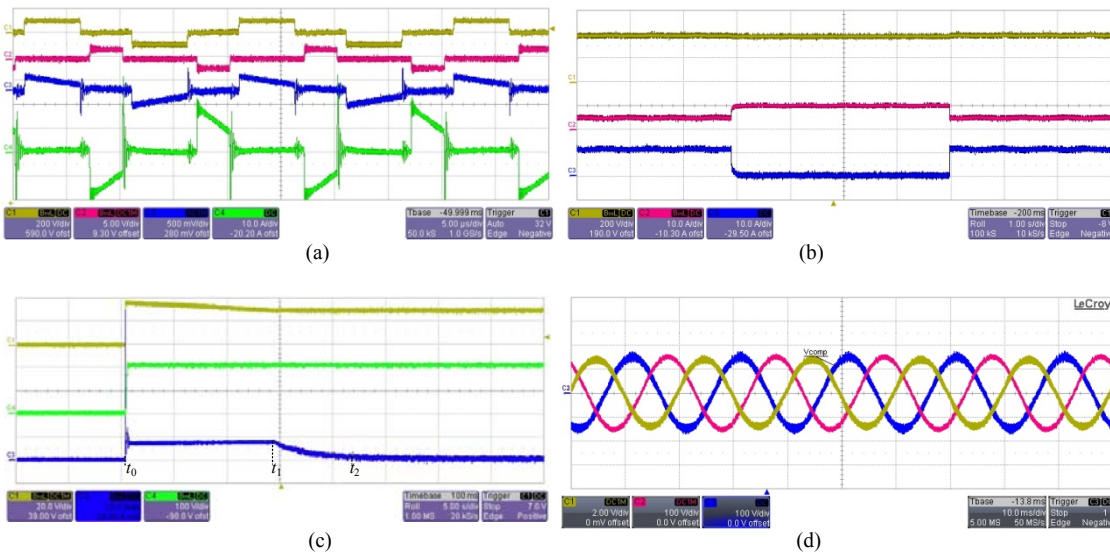


Fig. 4. Simulation results: fuel cell warm-up (T1), fuel cell transient period (T2), SC recharging (T3 and T5) and load disturbance (T4).





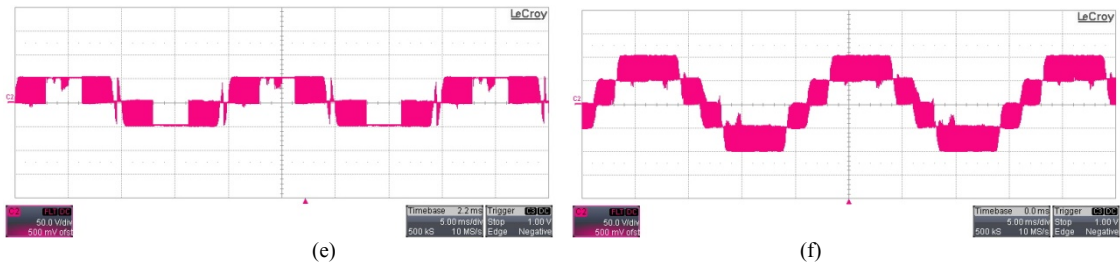


Fig. 5: Experimental results: (a) Ch1:  $v_{ab-DC}$  [200 V/div], Ch2:  $v_{cd-DC}$  [250 V/div], Ch3:  $i_{p1}$  [10 A/div], Ch4:  $i_{p2}$  [10 A/div]. (Time base:  $5 \mu\text{s/div}$ ); (b) Transient response with respect to the input current disturbances under conditions:  $V_{g1}=50\text{V}$ ,  $V_{g2}=30\text{V}$ . Ch1:  $v_{o-DC}$  [200 V/div], Ch2:  $i_{g1}$  [10 A/div], Ch3:  $i_{g2}$  [10 A/div]. (Time base:  $1\text{s/div}$ ); (c) Transient period, Ch1:  $v_{g2}$  [20 V/div], Ch3:  $i_{g2}$  [10 A/div], Ch4: output voltage  $v_{o-DC}$  [100 V/div]. (Time base:  $5\text{s/div}$ ); (d) three-phase output voltage,  $v_{AO}$ ,  $v_{BO}$  and  $v_{CO}$  ( $10\text{ms/div}$ ); (e) switched waveform for phase voltage  $v_{a0}$  ( $5\text{ms/div}$ ), and (f) switched waveform for line to line voltage,  $v_{l-l-ab}$  ( $5\text{ms/div}$ ).

#### 4. Conclusion

In this paper, an overview of power electronics converters and inverters for fuel cell hybrid power conversion system is given. Based on the previous research carried out at Electronics Group, Technical University of Denmark (DTU), a topology proposed here is composed of a dual-input dc-dc converter and three-level NPC inverter. The system can operate in both the stand-alone and grid-connected modes. The benefits of using super-capacitors have been shown clearly.

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