Simulation of Interleaved Current Fed Full Bridge Converter for Fuel Cell Electrical Vehicle

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ABSTRACT

Hydrogen fuel cell (HFC) is one of the renewable resources to address fossil fuel depletion and global warming. Its primary advantages are power is generated from renewable fuel hydrogen and the emission is only water. However, HFC supplies power in a slow dynamic response. In fuel cell electrical vehicle (FCEV), energy storage system (ESS), i.e. supercapacitor and battery, is required to immediately compensate the difference between load demand and power supply; the lifetime of HFC is affected by current ripple. In order to manage power flow between HFC and load, HFC is interfaced with a unidirectional DC-DC converter. The converter steps up the terminal fuel cell voltage and regulate the voltage before it is connected to the load. Among the proposed HFC DC-DC converters, interleaved DC-DC converter seems more suitable for FCEV application due to its advantages. When galvanic isolation is required, current fed full bridge converter receives significant consideration as the module of interleaved converter. This paper simulates interleaved current fed full bridge (ICFFB) converter and discusses the suitability of ICFFB for FCEV application.

Keywords: Hydrogen fuel cell, DC-DC converter, electric vehicle

INTRODUCTION

Demand for renewable resources is a result of fossil fuel depletion and concerns over global warming. In 2013, the transport sector accounted for 23% of the global Green House Gas emission, the second largest contributor (International Energy Agency, 2015). Fuel cell electric vehicle (FCEV) is a revolutionary technology that addresses this issue as it emits only water and does not need gasoline fuel.

Hydrogen fuel cell (HFC)/battery/supercapacitor architecture is found to be very fulfilling in the dynamic driving cycle in FCEV (Zandi et al., 2011). The HFC is unable to instantaneously fulfil all the load demand, especially during dynamic load cycle

(Thounthong, Tricoli, & Davat, 2014). Thus, the difference between load demand and power supply from HFC is compensated by energy storage system (ESS), i.e. supercapacitor and battery in FCEV. Moreover, ESS could be recharged by HFC or during regenerative braking. For ease of power flow management, HFC is interfaced with unidirectional DC-DC converter and each ESS component is interfaced with bidirectional DC-DC converter. Besides power flow management, the HFC DC-DC converter step ups and regulates HFC terminal voltage at designated level, since HFC terminal voltage is low and decreases when the HFC current supply increases. While HFC is vulnerable to low frequency ripple, the current source DC-DC converter for HFC is favourable (Wei & Fahimi, 2010). As high ripple current reduces HFC lifetime (Thounthong et al., 2014), the ripple on input current of HFC converter should be low.

In recent years, HFC current source DC-DC converters that have higher efficiency, power handling capability, step-up ratio, lower input current ripple etc. have been invented. The HFC DC-DC converters include non-isolated DC-DC converter (Al-Saffar & Ismail, 2015; Kuo-Ching & Jian-Ting, 2013; Sabzali, Ismail, & Behbehani, 2015), isolated DC-DC converter (Xuancai et al., 2005), interleaved converter (Hegazy, Van Mierlo, & Lataire, 2012; Kong & Khambadkone, 2007; Subsingha & Sarakarn, 2012) etc. Some of the non-isolated DC-DC converters are derived to further increase the step-up ratio without extreme duty cycle by inclusion of coupled inductor (Kuo-Ching & Jian-Ting, 2013), by integration of different DC-DC converters (Al-Saffar & Ismail, 2015; Sabzali et al., 2015) or by using cell multiplier (Rosas-Caro et al., 2015; Wuhua, Weichen, Yan, & Xiangning, 2010). Among the DC-DC converters, interleaved DC-DC converter is preferable for HFC application due to its many advantages of load sharing, have ripple cancellation effect on input current, higher reliability in supplying power etc. (Guilbert, Gaillard, Mohammadi, N'Diaye, & Djerdir, 2015; Kong & Khambadkone, 2007; Phatiphat Thounthong & Davat, 2010). Interleaved converter is constructed by paralleling the input of the identical modules (DC-DC converters) and the phase of the carrier signals are distributed evenly over a cycle and thus, DC-DC converters can be considered as a module for interleaving. When galvanic isolation is not necessary, classical boost converter with a hard switching technique can be considered (Hegazy et al., 2012; Subsingha & Sarakarn, 2012) due to ease of control and analysis. Galvanic isolation is required between supply and the load, full bridge converter is a more popular selection. Compared with push-pull DC-DC converter and half bridge converter, full bridge converter has lower switching stress, higher switch and transformer utilisation.

In this paper, an interleaved current fed full bridge (ICFFB) DC-DC converter consisting of four modules will be simulated in MATLAB. Full bridge converter is chosen as a module due to its advantages. The following sections will discuss in detail the operating principle of ICFFB DC-DC converter, the MATLAB model and the simulation results.

OPERATION OF ICFFB DC-DC CONVERTER

Figure 1 depicts ICFFB DC-DC converter that consists of four modules (Kong & Khambadkone, 2007). The first module has four switching states. As shown in Figure 2(a), during the first switching state SS1, all switches (S1-S2-S3-S4) is on and inductor L1 is charged (current i1

increases) while both capacitor C1 and C2 is discharged (each capacitor voltage decreases) supplying power to the load R. In switching state SS2 as shown in Figure 2(b), switches S3-S4 are off and switches S1-S2 are on. Inductor L1 is discharged (current i1 decreases), i.e. current i1 enters transformer Tx1 in negative cycle, to transfer energy to capacitor C2 (capacitor C2 voltage increases due to the charging) while capacitor C1 is discharging. Next, switching state SS3 is identical to switching state SS1. Finally, in switching state SS4 as illustrated in Figure 2(c), switches S3-S4 are on and switches S1-S2 are off. Inductor L1 is discharged, i.e. current i1 enters transformer Tx1 in positive cycle, to transfer energy to capacitor C1 while capacitor C2 is discharging.
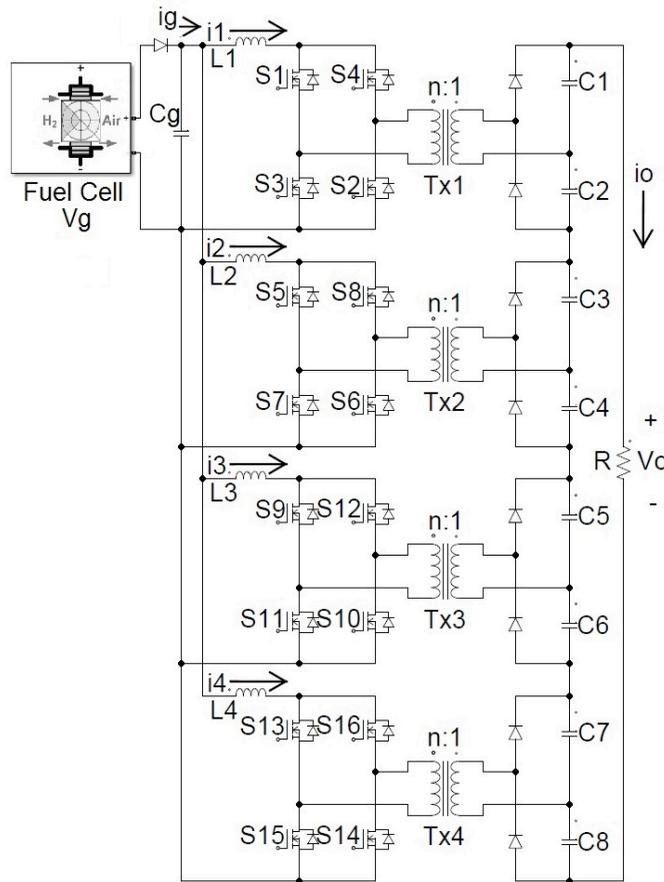

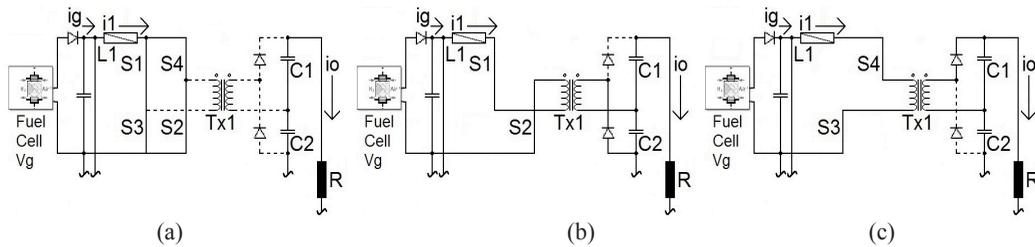*Figure 1*. ICFFB DC-DC converter (four modules)

Figure 2. Equivalent circuit for switching state (a) SS1/SS3 (b) SS2 (c) SS4

The first module has switching operation with repeat switching states of SS1, SS2, SS3 and SS4. Meanwhile, each of the remaining modules has similar switching operation that corresponds with the relevant switches, inductor, transformer and capacitors. For example, the second module has switching states involving switches S5-S6-S7-S8, inductor L2, transformer Tx2 and capacitors C3 and C4. 45° phase delay is imposed between the switching of the adjacent modules, i.e. first to fourth modules respectively has the phase delay of 0°, 45°, 90° and 135°. Contrary to Thounthong et al. (2009), the 45° phase delay (between the switching of the adjacent modules) is derived from equation (1), where m is the quantity of modules, since two switches are switched concurrently in each module.

$$\text{Phase Delay} = 2\pi/m \tag{1}$$

By the interleaving of the four modules, capacitor C1 to C8 are connected in series to provide output voltage Vo to load R. The small signal analysis of ICFFB DC-DC converter has been discussed by Kong and Khambadkone (2007). Equation 2 shows the voltage transfer ratio (Kong & Khambadkone, 2007), where Vo is the output voltage, Vcg is the voltage of capacitor Cg, m is the quantity of the modules, n is the transformer winding ratio (n:1) and D is the duty cycle of the switches. Quantity of modules boosts the voltage transfer ratio.

$$\frac{V_o}{V_{cg}} = m \times 2 \times \frac{1}{2n(1-D)} \tag{2}$$

ICFFB DC-DC CONVERTER MATLAB MODEL

MATLAB model ICFFB DC-DC converter is developed (see Figure 1). Table 1 shows the specification of the converter. The simulation is carried out in MATLAB with open loop system and FC block as the DC voltage source Vg. The FC block possesses characteristic curve of the commercially available fuel cell power module Nexa 1200 (one of the core components in the modular fuel cell training system - Nexa Training System) and the parameter is shown in Table 2 (Heliocentris Energiesysteme GmbH; Heliocentris Energiesysteme GmbH, 2012).

Table 1
ICFFB DC-DC converter specification

Voltage transfer ratio	Vo/Vcg	2
Inductor	L1 to L4	1.16mH
Capacitor	C1 to C8	470μF
Capacitor	Cg	33μF
Transformer winding ratio	n:1	5:1
Load	R	10Ω
Switching frequency	f	25kHz
Duty cycle	D	0.6

Table 2
Fuel cell block parameter (Nexa 1200)

Fuel cell voltage	Vg	18 – 36V
Rated output power	Po	1200W
Efficiency (at rated output power)	η	50%
Cell quantity	-	36

Carrier signal of first module to fourth module has the phase delay of 0°, 45°, 90° and 135°respectively to achieve 45° phase delay between the switching of the adjacent modules. Pulse width modulation signals are generated for the switching.

SIMULATION RESULT

Simulation has been carried for 0.4s and the result is shown in Table 3. The simulation waveforms are shown in Figure 3 and Figure 4. Figure 3(a) shows that the output voltage Vo is 65.39V with ripple 0.041V. Figure 3(b) shows the waveform of output current io 6.54A with ripple 0.0041A when the load is 10Ω. Figure 4(a) shows that the fuel cell voltage Vg 31.52V with ripple 2.61V. Figure 4(b) shows the input current ig 13.24A with ripple 0.021A. Figure 4(c) shows the waveform of inductor current i1, i2, i3 and i4 3.31A with ripple 0.12A. Figure 4(d) shows the waveform for voltage capacitor C1, C3, C5 and C7.

Table 3
Simulation result

	Average	Ripple
Output voltage Vo (V)	65.39	0.041
Output current io (A)	6.54	0.0041
Fuel cell voltage Vg (V)	31.52	2.61
Capacitor Cg voltage Vcg (V)	32.7	0.041
Input current ig (A)	13.24	0.021
Inductor current i1, i2, i3, i4 (A)	3.31	0.12
Capacitor C1/C3/C5/C7 voltage Vc1/Vc3/Vc5/Vc7 (V)	8.15	0.36

All inductor currents, each 3.31A, is equal to the input current ig 13.24A. This shows that the load current is equally shared among the modules. The ripple of each inductor current
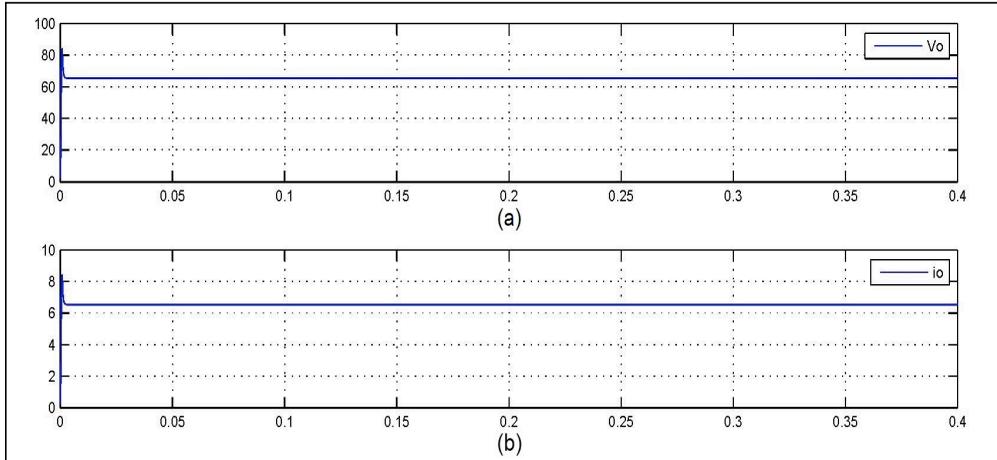

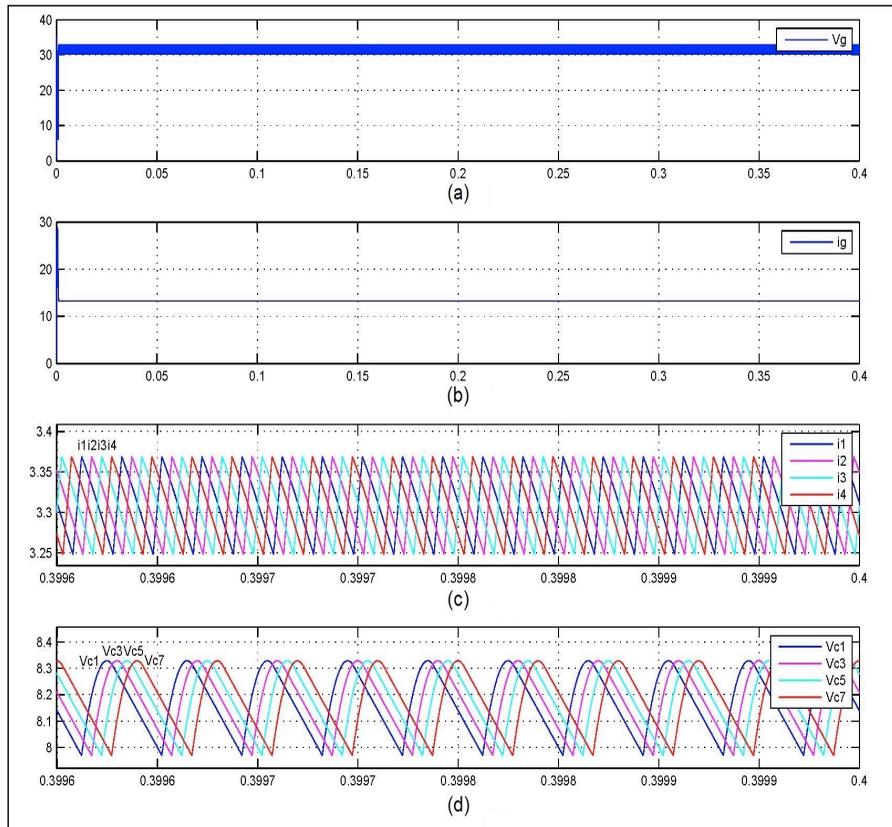*Figure 3.* Simulation result (a) output voltage Vo (b) output current io

Figure 4. Simulation result (a) fuel cell voltage Vg (b) input current ig (c) inductor current i1, i2, i3, i4 (d) capacitor voltage Vc1, Vc3, Vc5, Vc7

0.12A compensates each other and yields smaller ripple on the input current ig 0.021A, i.e. ripple cancellation effect. From Figure 4(d), the voltage of each output capacitor is 8.15V. The summation of all capacitors C1 to C8, each 8.15V, is close to the output voltage Vo 65.39V, suggesting the capacitor of smaller voltage rating could be utilised. Table 3 shows the ratio between output voltage Vo and capacitor Cg voltage Vcg is two, complying with the voltage transfer ratio that is expressed in equation (2).

CONCLUSION

This paper simulates ICFFB DC-DC converter that consists of four modules. From the simulation result, each module carries the same load current. Load sharing among the modules in the interleaved converter shows components of smaller rating could be used compared with non-interleaved converter, especially inductor and transformer. Besides, the ripple cancellation effect will minimise the HFC lifetime reduction. Interleaved converter depicts higher reliability in supplying power to the load. If one of the modules malfunctions, interleaved converter is still able to supply power at the total power rating of the remaining modules. The load sharing, ripple cancellation effect, higher reliability and the galvanic isolation between HFC and load are the advantages of ICFFB DC-DC converter for FCEV application.

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