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APPLICATION OF AN INTERLEAVED BOOST CONVERTER FOR FUEL CELL SYSTEMS

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ABSTRACT

A three-phase interleaved boost DC/DC converter is applied for fuel cell systems, of which the operation performance and lifetime are sensitive to its output current ripples. Fuel cells are essential energy sources in sustainable systems since they can convert stored energy in hydrogen to electricity when it is needed, so that they can enhance the robustness and adaptability of renewable energy systems. However, the low voltage of the fuel cells requires to be boosted to a suitable level for the application. Another issue with fuel cells is cell voltage imbalance due to insufficient fuel supply or high output current ripples. To overcome these issues, interleaved boost converters are good solutions to level up the output voltage while reducing the fuel cell output current ripples. Simulation results demonstrate that the interleaved converter effectively reduces the fuel cell current ripple by about 97% compared with fuel cell current ripple of the conventional boost converter. A 200 W three-phase hardware of interleaved boost converter is implemented to evaluate the ripple reduction of converter input current, which is the fuel cell current. The control of the converter is implemented in the real-time microcontroller of TMS320F28379D. A computer-based graphic user interface (GUI) has also been developed for real-time monitoring and controlling the designed interleaved converter, which provides ease of use for the users.

Keywords: Boost converter, current ripple reduction, fuel cell, interleaved converter.

1. INTRODUCTION

Nowadays, the global demand for energy has increased from about 350 exajoules in 2013 to about 400 exajoules in 2023 [1]. The majority of current electricity generation relies on the fossil fuels. Moreover, the burning of fossil fuels causes carbon dioxide emissions, which degrades air quality, causes environmental pollution, and contributes to the intensification of the greenhouse effect [2]. The issues related to environmental protection are receiving more attention recently.

Renewable energy is considered a promising alternative to fossil fuel-based energy. Clean energy is widely utilized for reducing emissions, mitigating adverse environmental impacts, and addressing climate change. The attention on renewable energy is increasing. In 2023, 31.2 exajoules of electricity were generated from green energy sources such as wind, solar, tidal, and hydropower [1]. However, a drawback of renewable energy is dependence on weather conditions and their power fluctuations. Therefore, renewable energy should come with an energy storage system to minimize the effects of power fluctuations and enhance the stability of the power system. The fuel cells, as a component of energy storage systems, can be considered as a friendly energy storage system. Fuel cells generate electrical energy from stored hydrogen (H_2), and oxygen (O_2) in the natural air while their side products are water (H_2O) and heat only [3]. Therefore, fuel cells not only reduce dependence on fossil fuels but also make a significant contribution to mitigation of greenhouse gas emission, one of the key effects of global climate change, through the direct conversion of chemical energy into electrical energy without a combustion process [4]. The hydrogen can be produced from surplus power of wind and solar energy with the electrolysis process or from coal gasification and natural gas reforming [5]. Hydrogen can be stored for long-term storage in high-pressure vessels or metal hydrides [6].

Although fuel cell technology offers many advantages, it also faces several challenges that need to be addressed. However, with the demand for hydrogen increasing, the cost of producing hydrogen and storing it is decreasing [7]. The main technical challenge of fuel cells is their low output voltage, high output current, and nonlinear voltage-current (V-I) characteristics. As the load current increases, the output voltage of the fuel cell tends to decrease due to voltage losses and internal electrochemical effects. Therefore, if a fuel cell supplies a load without an intermediate converter, the output voltage will vary significantly with the load level, making it difficult to maintain stable operation and forcing the fuel cell away from its optimal operating region.

Therefore, the use of a boost converter is necessary to step up the the fuel cell voltage to the suitable level while maintaining output voltage level under different load conditions, thereby ensuring proper operating conditions. The boost converter is a suitable choice for interfacing fuel cell with loads [8]. The study indicates that, compared with other DC/DC converters, the boost converters have good efficiency and require fewer active switches. This helps simplify the system design and reduce implementation costs, while effectively meeting the requirements of fuel cell systems for voltage step-up and voltage regulation. However, a notable limitation of this topology is significant ripple on the input current, which results in fuel cell current fluctuations [9]. Current ripple accelerates material aging, reduces energy conversion efficiency, and shortens the operating lifetime of the equipment. In addition, current fluctuations can cause cell voltage imbalance, negatively affecting the stability and reliability of the overall electrical system [3], [10]. A commonly used method to reduce current ripple is to increase the inductance value. However, large inductors usually lead to increased size and cost, and may also decrease the overall efficiency of the interfacing system. Therefore, many studies have proposed different methods to overcome the limitations of the conventional boost converter. Among these methods, the interleaved boost converter is considered a solution to address these issues. Compared with the traditional single-phase boost converter, the parallel multi-phase structure offers several advantages, including higher conversion efficiency, reduced current and voltage ripple, more even distribution of load current among phases, and improved system reliability and scalability [11].

In this paper, the operation of the parallel three-phase boost converter is analyzed. The effect of the interleaved converter on fuel cell current ripple reduction is evaluated for residential energy storage using a fuel cell of 7 kW [12] on the PSIM platform. A 200 W prototype interleaved converter is built to validate the effect on minimizing the output current of the fuel cell.

2. FUEL CELL AND INTERLEAVED BOOST CONVERTER

2.1. Residential hydrogen energy storage system

A hydrogen-based energy storage system for residential applications is a next generation of energy storage systems that can keep more than 40 kWh of energy in hydrogen form [12]. The simple structure of the residential hydrogen energy storage system is illustrated in Fig. 1. The system uses surplus solar energy to convert water to hydrogen by electrolysis and stores it in metal hydride storage vessels. The hydrogen is retained in these vessels for long duration. When the demanded load is higher than the photovoltaic power and the battery level, state of charge (SoC), is high enough, the integrated battery firstly discharges to assist the power to the load. Then the fuel cell is activated to convert the hydrogen to electricity when the demand load is still high, but the battery SoC is low. With this configuration, the battery capacity does not need to be high, and the fuel cell works as the principal component of the energy storage systems.

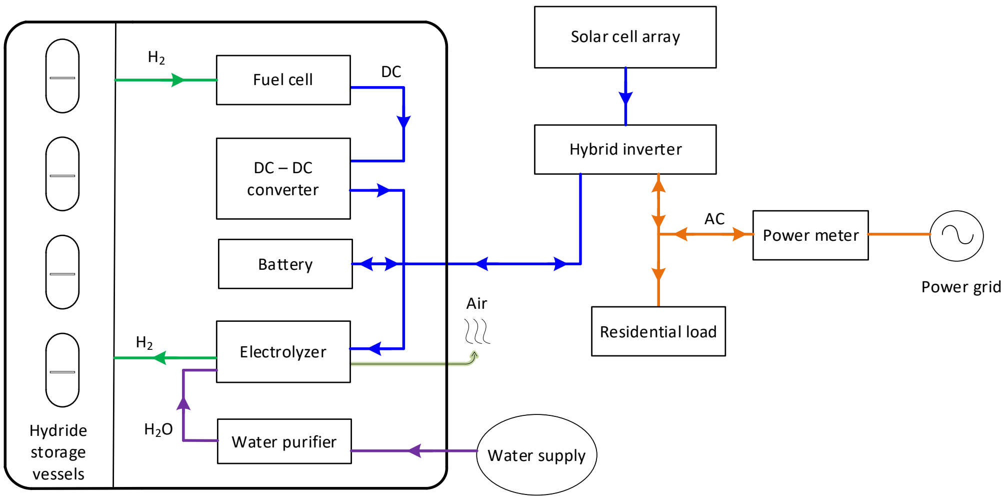

Fig. 1. A simple structure of residential hydrogen energy storage system.

The hydrogen storage system can take grid power to convert water to hydrogen during off-peak prices and generate electricity from hydrogen to supply to the grid during peak prices of the electricity if the power grid allows the power from the hydrogen energy storage system. In addition, the hydrogen storage system can assist the operation of the virtual power plant (VPP), which contributes flexibility and reliability of the power system [13].

2.2. Fuel cell

A fuel cell is a type of energy converter that produces electrical energy from the chemical energy of a fuel through electrochemical oxidation and reduction processes, without involving an intermediate combustion process [14]. Consequently, fuel cell efficiency is quite high and it can reduce pollutant emissions compared with conventional power generation technologies. Structurally, a typical fuel cell consists of the anode, the cathode, and the electrolyte membrane. Among the various fuel cell types, the proton exchange membrane (PEM) is the most widely adopted owing to its high proton conductivity and suitability for operation at relatively low temperatures.

Although fuel cells have a complex structure, their operating principle is fairly simple. The hydrogen gas (H_2) is supplied to the anode, and the cathode is provided with oxygen (O_2). At the anode, the supplied hydrogen is electrochemically oxidized into positive hydrogen ions (H^+) and electrons (e^-). The positive hydrogen ions are transported across the electrolyte membrane toward the cathode, whereas the electrons are blocked due to the insulating properties of the electrolyte. Because electrons cannot pass through the electrolyte, they flow through the external circuit connecting the two electrodes, thereby generating an electric current that supplies the load [15]. At the cathode, the supplied oxygen gas accepts protons (H^+) and electrons (e^-), forming water molecules (H_2O), which are the sole by-products of the process [16].

2.3. Interleaved boost converter

The interleaved boost converter is designed to improve efficiency and reduce voltage and current ripples at both sides of the converter. In this study, the converter is implemented with a three-phase configuration; its simplified schematic is shown in Fig. 2. Each phase has the same structure and operates on the same principle, consisting of an active switch (Q_x), an inductor (L_x), and a diode (D_x), where x = {1, 2, 3}. The three phases are controlled by PWM signals with identical duty cycles but phase-shifted by 120°. Specifically, within one switching period T, the MOSFET of phase 1 conducts starting at 0°, the MOSFET of phase 2 begins to conduct after a 120° phase shift, corresponding to T/3, and the MOSFET of phase 3 conducts starting at 2T/3. The pulse width depends on the duty cycle of the control signal [17]. After completing one switching period, the process repeats cyclically with the same switching sequence. The same duty cycle is applied to all three phases to assist the phase current balancing. However, parameter tolerances, which can cause phase current imbalance, are beyond the scope of this research.

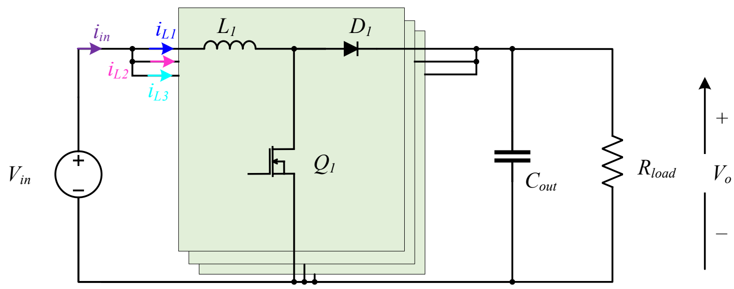

Fig. 2. Simplified schematic of the three-phase interleaved boost converter.

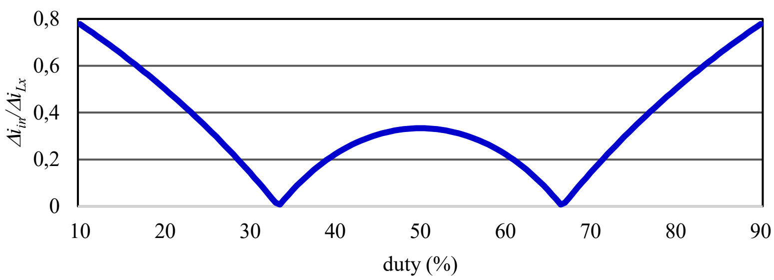

Fig. 3. Relationship between input current ripple to inductor current ripple ratio across various duty cycle in three-phase interleaved boost converter.

As illustrated in Fig. 2, the interleaved converter consists of three parallel phases, where L_1, L_2, L_3 are the inductors of phase 1, phase 2, and phase 3, respectively. The MOSFET Q_1, Q_2, Q_3 act as the switching devices for each phase and D_1, D_2, D_3 are the stocky diodes. V_s, V_o, and R_{load} are the input voltage, output voltage, and load, respectively. During a switching cycle period, when the MOSFET of a given phase turns on and conducts, V_i applies to the inductor L_x, the current inductor, i_{Lx}, as well as stored energy in the inductor increases. When the MOSFET turns off, stored energy releases to conduct D_x for applying a voltage of $V_i + V_{Lx}$ to the output capacitor, C_{out}, and load R_{load}. Since the three-phases operate with a 120° phase shift, the input current can be expressed

$$i_{in} = i_{L1} + i_{L2} + i_{L3} \tag{1}$$

where i_{in}, i_{L1}, i_{L2}, and i_{L3} are input current, currents through inductor L_1, L_2, and L_3, respectively. The input and output currents exhibit reduced ripple as shown in Fig. 3, where the ripple ratio of the input and inductor currents depends on the duty cycle. Consequently, the total current supplied to the load is maintained in a nearly continuous manner, significantly reducing current ripple compared to a single-phase boost converter. The increased phase number of interleaved converter helps amplifying the benefits such as current ripple reduction and improved efficiency. However, it also introduces significant complexity in the control system. Therefore, the three-phase interleaved converter is chosen.

Under normal operating conditions and continuous conduction mode (CCM) of the converter, the ratio between the output and input voltages is expressed as

$$\frac{V_o}{V_i} = \frac{1}{1-d} \tag{2}$$

where d denotes the duty cycle of the switching signal.

3. SIMULATION RESULTS

The structure of the simulation is illustrated in Fig. 4. A DC voltage power supply with a resistor emulates the role of the fuel cell, of which the output voltage depends on the output currents as the I-V curve of the fuel cell [14]. The three-phase interleaved boost converter is utilized to convert the electric energy from the fuel cell to the buffer battery, where the equivalent circuit is a DC voltage with a serial resistance or internal battery resistance. To simplify the evaluation conditions, the input capacitance of the three-phase interleaved boost converter is negligible. The parameters of the simulation are listed in Table 1.

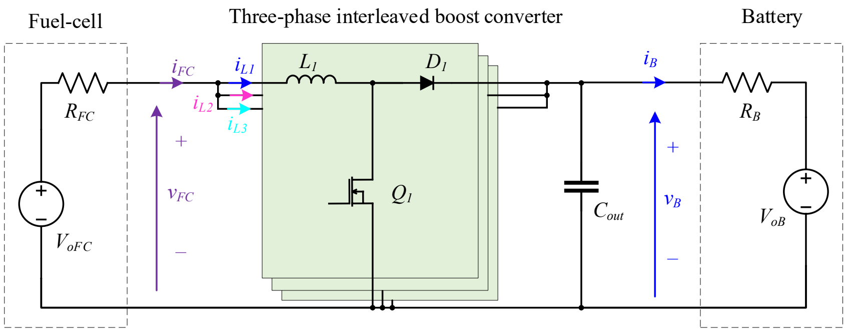

Fig. 4. The structure of the simulation on fuel cell charging a battery

Table 1. Parameters of the simulation system

Parameters	Values
Fuel cell	Nedstack FCS 7-XXL
Fuel cell open voltage (V_{oFC})	46.6 V
Maximum current	230 A
Switching frequency	50 kHz
Inductance	20 μH
Output capacitance	200 μF
Battery voltage (V_{oB})	51.5 V
Battery internal resistance (R_B)	20 $m\Omega$

Fig. 5 presents the simulation results of a fuel cell charging a battery through the three-phase interleaved converter. The battery charging current, I_B, is the control signal, which is shown in Fig. 5a. The reference value of the battery current is varies from about 30 A at the beginning and gradually increases to 60 A, 90 A, and 120 A and the feedback battery current is well followed the reference one for the value 30 A, 60 A, 90 A, and 120 A, respectively. With the increase in the output current of the interleaved converter, the input current or the fuel cell current i_{FC} increases to 33.3 A, 87 A, 142.6 A, and 215 A, respectively, as shown in Fig. 5b. It verifies that the fuel cell current need follows the demand of the load during the operation. As shown in Fig. 5c the fuel cell voltage is gradually reducing to 39.08 V, 36.4 V, 33.7 V, and 30.2 V while its output current is increasing, which is similar to the fuel cell datasheet [18]. The battery voltage is slightly increasing while the charging current increases from 52 V to 54 V as shown in Fig. 5d.

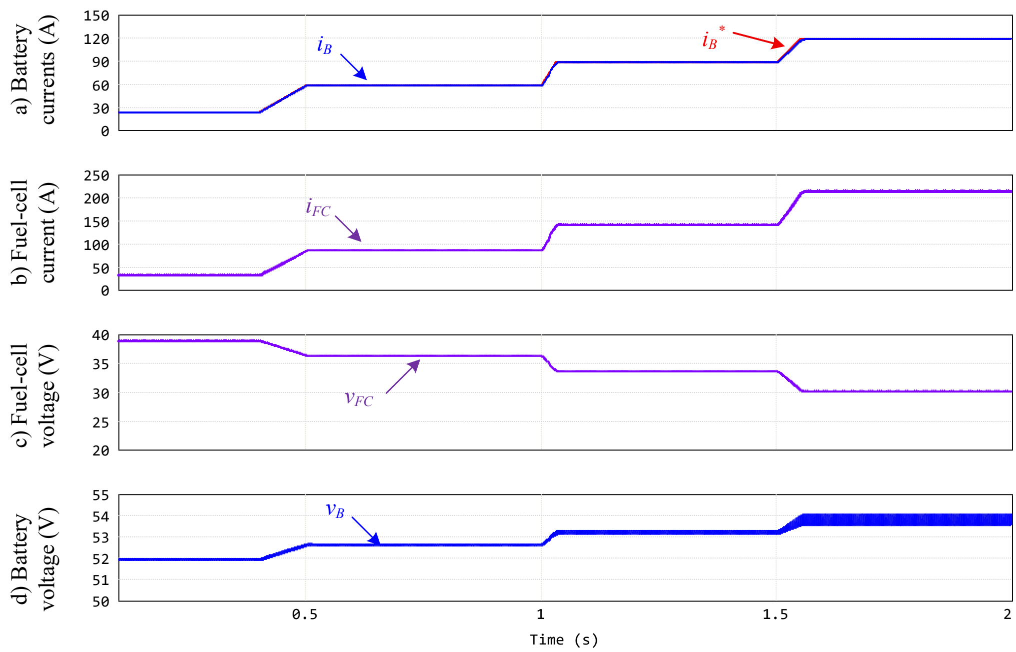

Fig. 5. Simulation results of the interleaved converter for fuel cell–battery interfacing. a). battery reference and feedback currents. b) fuel cell current. c) fuel cell voltage. d) battery voltage.

The fuel cell current with the operation of the interleaved converter is shown in Fig. 6. The fuel cell output current of 87 A is also the input current of the interleaved converter. With the operation of the interleaved converter, the inductor currents, i_{L1}, i_{L2}, and i_{L3} are about 29 A and have the phase disposition 120^o each other as shown in Fig. 6b. Their current ripples of about 10 A, but their phase shift of 120^o helps the ripple of fuel cell current, i_{FC}, is about 1.0 A as shown in Fig. 6a. The low ripple of the fuel cell current assists the operation of the fuel cell more stable and better effect on the cell voltage imbalance [3].

For comparison to the three-phase interleaved converter, the testing circuit in Fig. 4 is evaluated with replacement by a conventional boost converter. Since there is only one phase and one inductor, the waveform of the fuel cell current is the same as the inductor current, as shown in Fig. 7. It is noted that the average current is 87 A, as that of Fig. 6a, but the ripple of the fuel cell current in Fig. 7 is about 33 A. The high value of the current ripple affects the cell voltage imbalance as well as the lifetime of the fuel cell. Therefore, the three-phase boost converter helps reduce the fuel cell current significantly, and as a result, the fuel cell issues, such as the cell voltage imbalances, can be minimized.

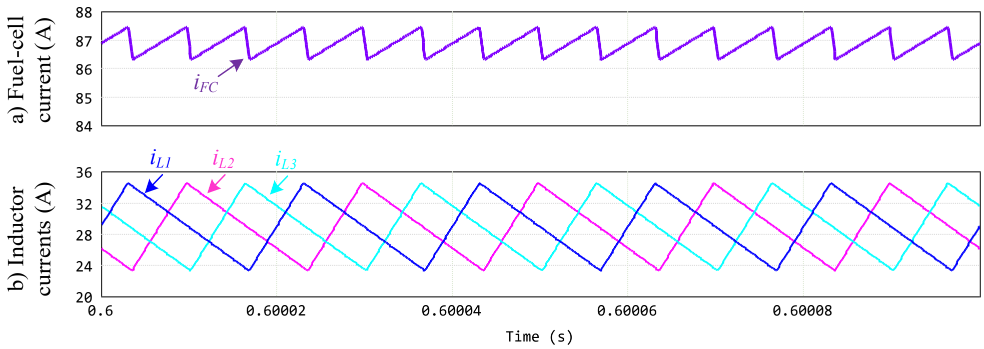

Fig. 6. The simulation results of the fuel cell current and inductor currents with interleaved boost converter

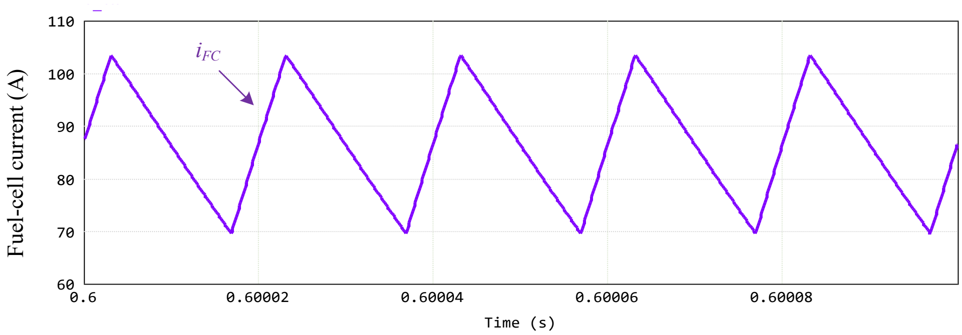

Fig. 7. The simulation result of the fuel cell current with a conventional boost converter.

4. EXPERIMENTAL RESULTS

The experimental setup of the system of a fuel cell charging a battery in Fig. 4 is carried out to demonstrate the validity of the evaluation, as illustrated in Fig. 8, and the parameters of the experimental setup are listed in Table 2. A DC power supply and an equivalent resistance of 2 Ω are utilized to emulate the fuel cell voltage. The emulated V–I characteristic is derived from the V–I curve of a NedStack fuel cell [18]. The interleaved converter is controlled by the microcontroller of TMS320F28379D. The power section of the converter is isolated from the control section by the isolated gate driver of HCPL-3120 and the isolated amplifier of HCPL-7800 to transfer the feedback signals to the microcontroller. The feedback values are used to control the battery charging current or fuel cell current, as well as voltage if needed.

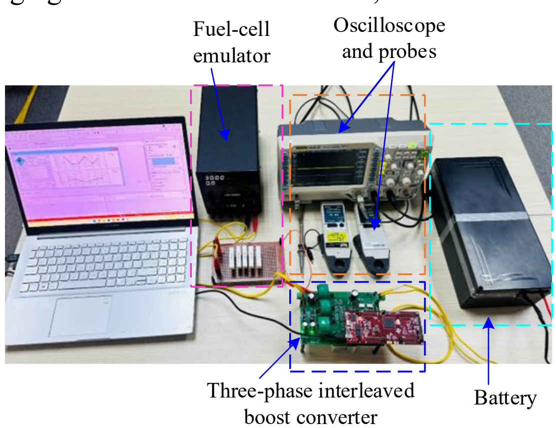

Fig. 8. Experimental setup

Table 2. Parameters of the experimental setup

Parameters	Values
Fuel cell open voltage (V_{oFC})	45 V
Fuel cell resistance (R_{FC})	2 Ω
Switching frequency	50 kHz
Inductance	50 μH
Switching device	STF40NF20
Diode	MBR20200CT
Output capacitance	100 μF
Battery open voltage (V_{oB})	51.5 V

Fig. 9 illustrates the fuel cell current supplying the three-phase interleaved converter to charging a battery. The average fuel cell current is about 4.5 A, and the ripple is about 1 A. The period of the current fluctuations is about 6.67 μs, which is one-third of the switching period of 50 kHz, demonstrating the correction of the testing hardware. The currents of each inductor in the interleaved converter are shown in Fig. 10. Each current fluctuates at the frequency of 50 kHz, which is the same as the switching frequency. The inductor current ripple is about 3 A and has a phase disposition of 120^o. These contribute to the low ripple on the total input current of the interleaved converter, as shown in Fig. 9. The low ripple of the input current causes the low fluctuations in the fuel cell current, which leads to better performance and improves the cell voltage imbalance issue.

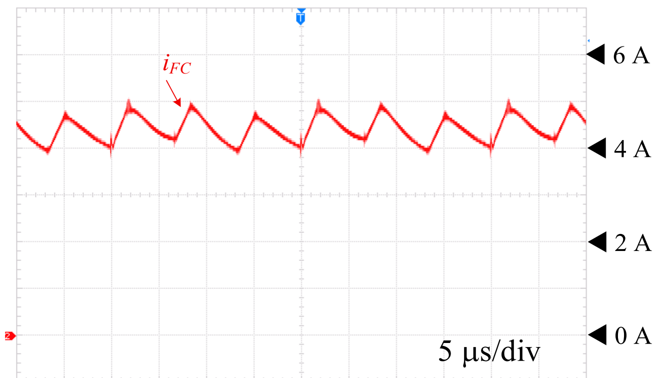

Fig. 9. Experimental results of the fuel cell current

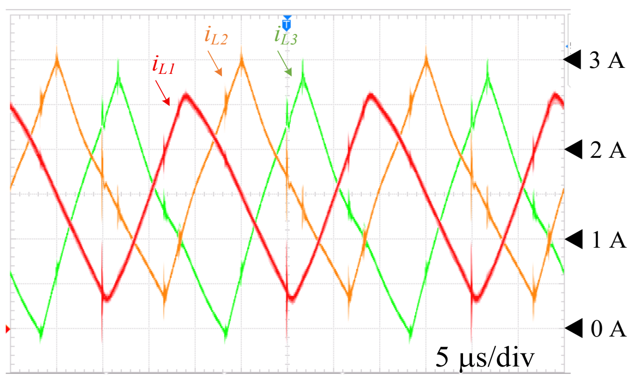

Fig. 10. Experimental results of the inductor currents of the three-phase interleaved converter

The test of changing the battery current, I_B, is carried out on Fig. 11, where the demanded battery current is increased by 0.5 A each period of about 4 seconds. The increase of the battery charging current from 0.5 A to 3 A causes the increase of the converter input current from about 0.7 A to about 8 A. During the increase of the output current of the interleaved converter, the voltage v_{in} as well as the voltage v_{out} of the emulate fuel cell reduced from about 45 V to about 30 V, which indicates similar I-V characteristics of the fuel cell.

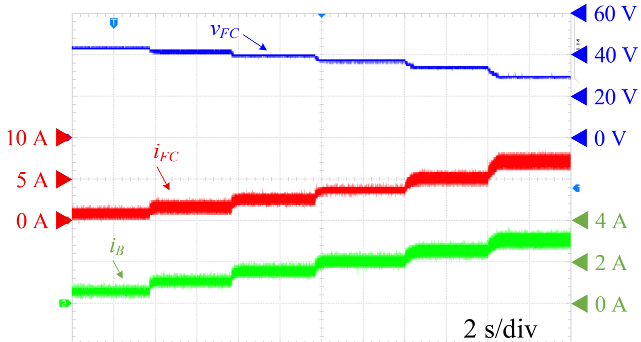

Fig. 11. Experimental results of a fuel cell charging a battery.

In addition, a graphic user interface (GUI) has been built for communication with the real-time microcontroller of TMS320F28379D. The GUI helps the operator to easily monitor and control the interleaved converter in various operation modes. By utilizing the high speed UART communications, the GUI can read the value of the voltages and currents of the converter every 100 ms and display the value in number format and graphs as shown in Fig. 12. In these graphical representations, the horizontal x-axis denotes time with a scale of 10 seconds, while the vertical y-axis of the upper plot indicates voltage in volts (V), and the y-axis of the lower plot represents current in amperes (A). At the same time, the GUI can send the operation method as output voltage control mode or output current control mode, as well as the reference value of each control mode. The GUI helps the operators eliminate the need to understand the coding of the real-time microcontroller and the need for an oscilloscope and probes during the operation.

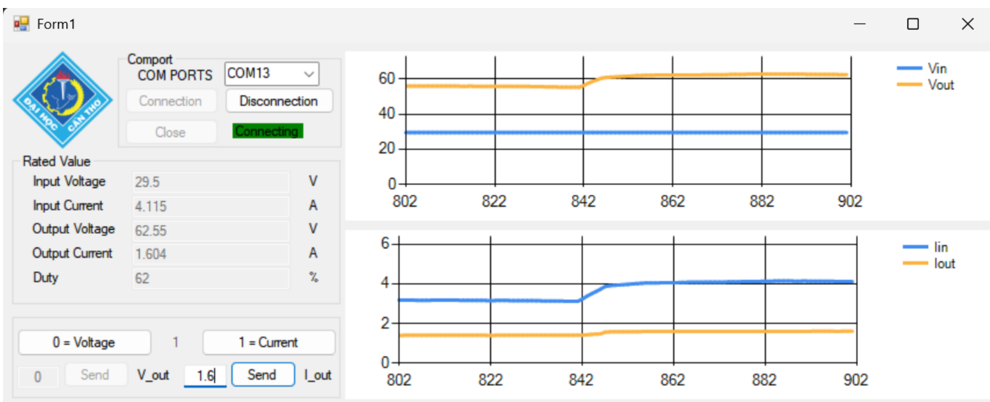

Fig. 12. A graphic user interface for monitoring and controlling the interleaved converter.

5. CONCLUSIONS

The three-phase interleaved boost converter is verified to support the fuel cell for a residential application. The interleaved converter can help increase the dependency of the output voltage on the output current to a suitable voltage level and a stable output voltage. In addition, the interleaved converter helps minimize the current ripple of the fuel cell, which assists the operation performance and lifetime of the fuel cell. Specifically, the fuel cell current ripple is reduced by about 97% compared to that of conventional single-phase boost converter. The simulation of an actual residential hydrogen energy storage system is carried out to evaluate the effectiveness of the interleaved converter. A 200 W prototype of the three-phase converter with isolation capability between the power section and control section was built to verify the effectiveness of the interleaved converter. A GUI is built to minimize the effort of the operator for monitoring and controlling the three-phase interleaved converter.

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