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4 Phase Interleaved DC Boost Converter for PEMFC Applications

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Abstract

Proton Exchange Membrane Fuel Cells (PEMFC) is a versatile renewable energy sources that can be used in a wide range of applications. This paper presents a basic principle of PEM Fuel Cell, its operation and control when it connects with the interleaving 4 Phase DC Boost Converter. The power rating of DC Converter in this paper is about 1.2 kW., input voltage 26 V, output voltage 60 V and output current 46 A. The result shows that the operation of 4 Phase Interleaved DC Converter together with 1.2 kW of PEM Fuel Cell has a good performance. The efficiency of the overall system is around 85 – 95% when the experiment is set to a constant output voltage.

Keywords: PEMF; Interleaved Technique; DC Converter

1. Introduction

Fuell Cell (FC) was invented firstly in 1839 by Sir William Robert Grove. It is an Electro-chemical Energy Conversion Device which produces an electrical energy from chemical reaction by an appropriated mixture of Hydrogen and Oxygen. The byproduct of fuel cell is water (H_2O) and heat.

In the process of fuel cell, electrical energy can be produced directly without causing any pollution such as CO_2. And it has more efficient than combustion engine about 1-3 times depending on the type of fuel cells [1]. Proton Exchange Membrane Fuel cell (PEMFC) is used in this article. In PEMFC, the thin polymer sheet is used as an electrolytic in order to operate in low temperature (about 80°C). It also has an advantage in light-weight, gives high efficiency to the cell. PEMFC can produce a large electrical power

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from 50-250 kW [2]. However, it needs a high purified of fuel and well catalyst such as Platinum which is expensive.

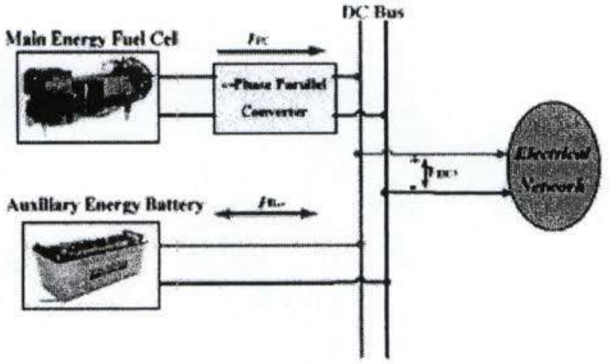

Fig. 1. Example of hybrid system between fuel cells and another energy source

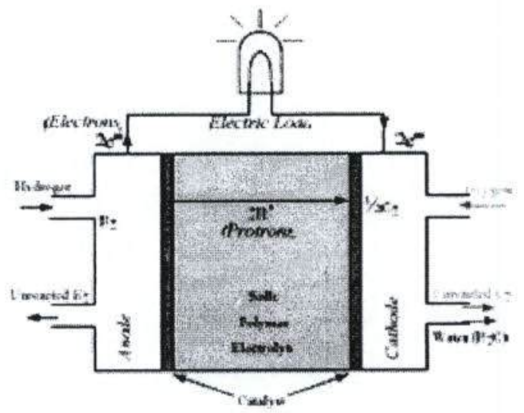

Fig. 2. Basic construction of the PEM Fuel Cell

However, Fuel Cell is an electrical source that can not keep any longer in an electrical energy. Thus, when Fuel Cell is applied into any projects such as an Electrical Vehicle (EV), the hybrid technique between fuel cell and another bi-directional DC Source (e.g. Battery) have to be considered. The example of Hybrid systems application between Fuel Cell and battery is shown in Fig. 1.

2. Proton Exchange Membrane Fuel Cell

2.1 Principle of PEMFC

The basic components of PEM fuel cell is anode terminal, Cathode terminal, Electrolyte solution and Catalyst, which the PEM fuel cell construction is shown in Fig. 2.

When the pressurized of hydrogen gas is moved into PEM fuel cell at anode side. Proton (H^+) and Electron (e^-) may be generated by the reaction of the collision between Hydrogen gas and the Catalyst. Thus, Electron (e^-) will flows into the external circuit as a DC current, and then flows back into fuel cell at Cathode terminal. This is due to the Electron (e^-) cannot pass through the Electrolyte inside the PEM fuel cell. Beside, Proton (H^+) can pass through the Electrolyte into Cathode terminal. The chemical reaction at the anode terminal of the fuel cell is

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

In the same time, the pressurized of Oxygen is also moved into PEM fuel cell at cathode side. The combination of Electron (e^-), Proton (H^+) and Oxygen (O_2) may produces the purified water, which has to drained out from the fuel cell as shown in Figure 2. The chemical reaction can be written as

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

The result of the reaction between Anode and Cathode terminal can be described as follows

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Heat + Electrical\ Energy \quad (3)$$

Thermo-dynamic Output Voltage (E) of every single cell of PEMFC could be determined by Gibb's Free Energy Change ((ΔG) which is 237 kJ/mol. at standard operating temperature 25°C.

$$E = -\frac{\Delta G}{nF} = 1.23\ V. \quad (4)$$

when F is a Faraday's constant. (96,485 Coulombs)
n is number of an electron (here is 2 electron).

By theoretical, output voltage of each cell of PEM Fuel Cell (E) must be 1.23 V. But in practice, no-load voltage at each cell is about 0.5 – 0.8 V., due to the voltage drop inside cells of the PEMFC. Therefore, it is necessary to connect a lot of cells in series circuit (called as FC stack) for various applications in order to satisfy the desired output load voltage.

2.2 Control scheme of the PEMFC

From Fig. 3, it shows the basic control scheme of the 1.2 kW 47 cells PEM Fuel Cell., which its no-load output voltage is about 37.6 V. at the working temperature 60°C.

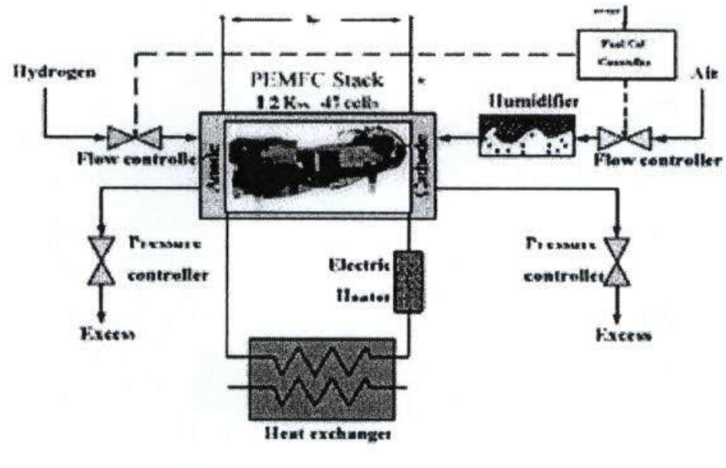

Fig. 3. The basic control scheme of the PEM Fuel Cell

3. DC Converter for Fuel Cell Applications

3.1. 4 phase Interleaved DC Boost Converter

DC Boost Converter is commonly used together with the Fuel Cell, in order to step up and regulate the DC output Voltage of the system. Beside, it has another advantage in the reduction of number of cells that used in PEM Fuel Cell [4]. DC Converter that is presented in this paper is a 4 Phase Interleaved DC

Boost Converter, which is shown in Fig. 4. Its operation is to step up PEM Fuel Cell output voltage (26 V) to 60V, which is suitable for various applications.

The proposal of 4 Phase Interleaved DC Boost Converter is to reduce the size of inductor (L) that used in DC Converter circuit. By this reason, it reduces the response of high frequency which may produces by a large size of inductor. Besides, it also results in smaller amount of a ripple of the DC Converter output voltage. And the size of some components such as filtering circuit, capacitors, diode and etc. may also be reduced accordingly. The equation of current in Fig. 4 is

$$i_{FC} = i_{L1} + i_{L2} + i_{L3} + i_{L4} \tag{5}$$

3.2. Design of DCBoost Converter

The function of DC Boost Converter is to step up DC voltage, which the power ratings of the converter are as follows [5]

$$P_{in} = V_{in}.I_{in} \tag{6}$$

$$P_{out} = P_{in}.\eta \tag{7}$$

$$I_{out} = P_{out} / V_{out} \tag{8}$$

when P_{in}, V_{in} and I_{in} are rated power, rated voltage and rated current of the PEM Fuel Cell
V_{out}, I_{out} are rated output voltage and rated output current of DC Converter
P_{out} is rated output power of DC Converter
η is the system efficiency.

Duty Cycle (D) of the converter can be defined as

$$D = 1 - (V_{in}/V_{out}) \tag{9}$$

Thus, rms. value of the switching current $(I_{S,rms})$ is

$$I_{S,rms} = I_{in}.\sqrt{D} \tag{10}$$

The size of diode, which works as a part of filter and together blocking a reverse current can be determined by the diode rms. current $(I_{D,rms})$ as follows

$$I_{D,rms} = I_{in}.\sqrt{1-D} \tag{11}$$

The size of capacitor (C_{Bus}) is

$$C_{Bus} = \frac{I_{out}.D}{\Delta V_{out}.f} \tag{12}$$

when ΔV_{out} is ripple factor of the output voltage

f is switching frequency that used in the Converter

The size of inductor (L) is

$$L = \frac{V_{in}.D}{\Delta I_L.f} \tag{13}$$

when ΔI_L is ripple factor of inductor current when switch is on.

By design, power rating of PEM Fuel Cell is 1.2 kW., 26 V, 46 A. DC Converter has to design for output voltage 60 V at switching frequency 25 kHz, which its efficiency is approximate 90%. The value of ΔV_{out} and ΔI_L is limited at 2% and 12%, respectively.

From equations (6) to (13), we determine the duty cycle and value of components, which is shown in Table 1.

Table 1. Duty Cycle and value of components for 4 Phase Interleaved DC Boost Converter

Duty Cycle (D)	0.57
Bus Capacitor (C_{Bus})	681.8 μF
Inductors (L1, L2, L3, L4)	214.8 μH.
Power MOSFET (S1, S2, S3, S4)	IRFP264N (250V, 38A)
Power Diode (D1, D2,D3, D4)	RuRG3020 (200V, 30A)

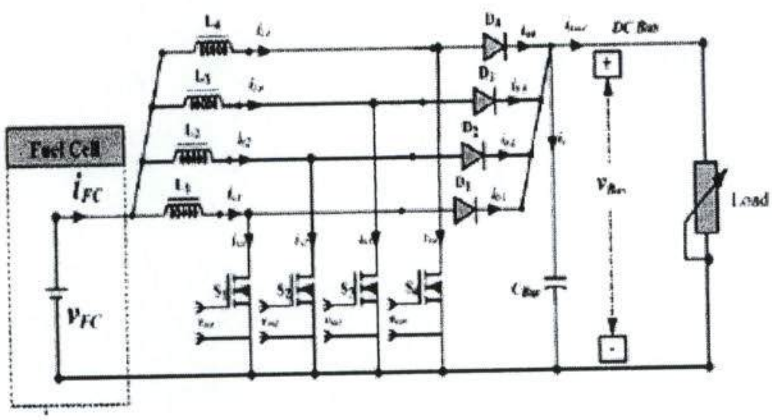

Fig. 4. The 4 Phase Interleaved DC Boost Converter

3.3. Closed loop current control of the 4 Phase DC Converter

The system that presented in this paper is regulated power output by closed loop current controlled of the 4 Phase Interleaved DC Converter as shown in Fig. 5.

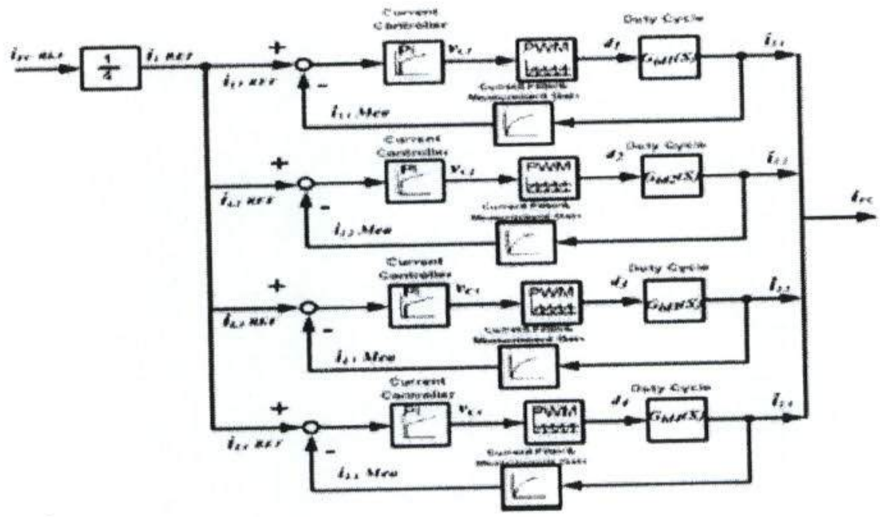

Fig. 5. Closed loop current control scheme for the 4 Phase Interleaved DC Boost Converter

From Fig. 5, inductor current (i_L) will transformed into a feedback signal ($I_{L\text{-}Mea}$) through a first order filter in order to reduce noises, and then compares with a reference signal (i_{L_REF}), which called as "Error signal". After it passed a PI controller, it is suitable to use as a control signal in order to generate a switching signal by a well-known PWM method for Power MOSFET in the DC Converter.

However, the angle of control signal for all four switches (Power MOSFET) is always shifted by 90° simultaneously, comparing to another switches in the circuit.

4. Experimental results

The experiment was set up as shown in Fig. 6. PEM Fuel Cell is NEXA1200 power module 1.2 kW, 26V, 46A, (47 cells) from Heliocentris Energie systeme GmbH, Germany. The 4 Phase DC Boost Converter was controlled in real-time via dSPACE1104 interfacing. Electronic load was used in this experiment in order to control output current yields to a constant load voltage at 60V. (Assume as working in a constant voltage application). However, I_{L_REF} will set from 0A. to rated current value of PEMFC, then observe the system efficiency (η). The experiment result is shown in Table 2 and Fig. 7.

Table 2. The relationship of i_{FC}, v_{FC}, i_{Bus}, v_{Bus} and efficiency of the system

i_{L_REF} [A]	$i_{in}(i_{FC})$ [A]	$v_{in}(v_{FC})$ [V]	i_{Bus} [A]	v_{Bus} [V]	η [%]
5	5.2	26.5	2.4	60	95.69
10	10	26.2	4	60	91.60
15	15.4	25.8	6	60	90.60
20	21	25.4	8	60	89.98
25	27	25.2	10	60	88.18
30	31	24.5	11.5	60	90.84
35	36	24.1	13.2	60	91.28
40	41	23.7	14.2	60	87.68
45	46	23.5	15.4	60	85.47

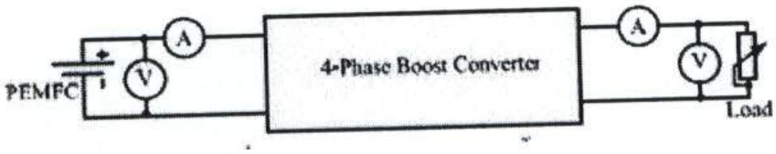

Fig. 6. Test diagram of the proposed DC Converter

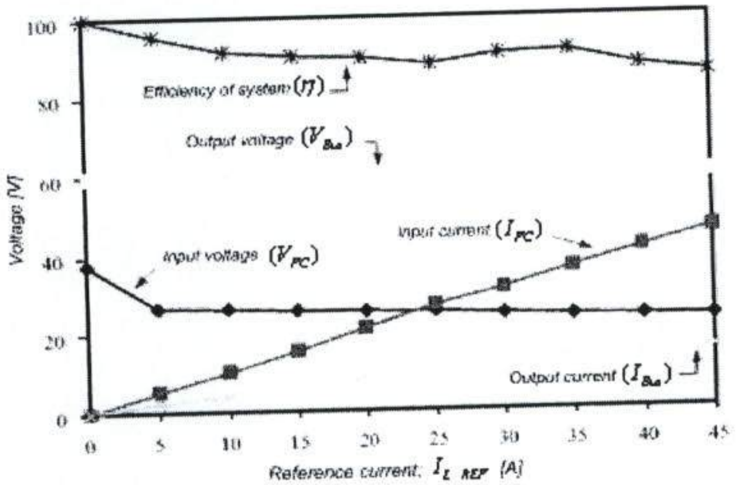

Fig. 7. The Profiles of V_{FC}, I_{FC}, V_{Bus}, I_{Bus} and η of the system in various load conditions

At no-load condition of the Fuel Cell operation, output voltage (which is input voltage of the DC Converter; V_{FC}) is 37.6V. And at full load condition of the fuel Cell, V_{FC} is lower down to 23.5 V, while the output current (I_{FC}) is rising up to its rated current 45 A. V_{FC} and I_{FC} will flow into the DC Converter as an input power.

The performance of the proposed DC Converter was tested by observing the input current I_{FC}, output current (I_{Bus}) and efficiency of the Converter from the setting of I_{L_REF} from 0 A. to 45 A. The result shows that input current (I_{FC}) of the Converter is converged to the reference value I_{L_REF}. Output current of the system (I_{Bus}) is reasonable related to the input current (I_{FC}). It yields a high efficiency of the system, which is round 85 to 95% as shown in Table 2.

In Fig. 8, inductor current (i_{L1}, i_{L2}, i_{L3}, i_{L4}) and input current (i_{FC}) waveforms of the 4 Phase Interleaved DC Boost Converter are shown (here, displays only i_{L1}, i_{L2}, i_{L3} and i_{FC}). As seen above, the phase angle of inductor current that flows in each coil is shifted about 90° to each others. When I_{L_REF} is set to 20 A., input current of the DC Converter (i_{FC}) is 21 A. (by approximately 20 A.) Therefore, the inductor current that flows in each coil is 5.25 A., and the output current (i_{Bus}) is approximately 8 A.

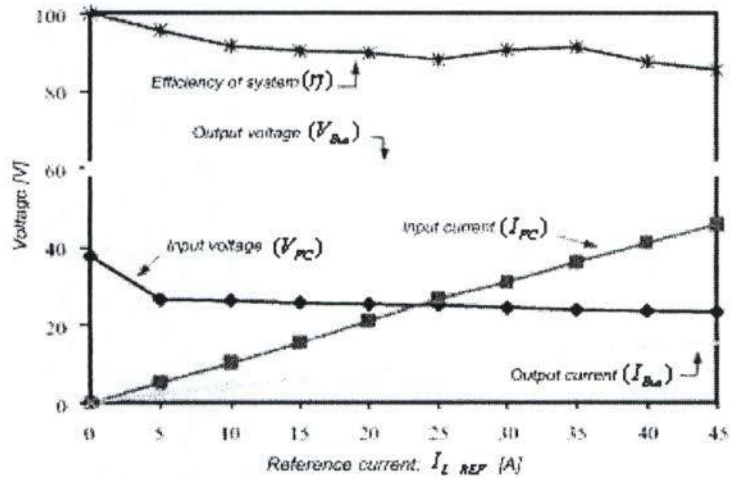

Fig. 8. Waveform of inductor currents (i_{L1}, i_{L2}, i_{L3}) and input current (i_{FC})

5. Conclusions

This paper presents a basic operation and control scheme of the Proton Exchange Membrane Fuel Cell (PEMFC), together with a design of the 4 Phase of Interleaved Technique for DC Boost Converter and its control. The proposed DC Converter is suitable and convenience in the use with PEM Fuel Cell due to its small scale and easy to control.

The experiment results show that the efficiency of the over all of the system is around 85 – 95% which is adequately high for various applications. However, the experiment is set up as a constant system output voltage, which may suitable for a constant voltage application. In the future, hybrid system of PEMFC with another bi-directional DC source is also in the view of interested.

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