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4-Phase Interleaved Technique Boost Converter for Fuel Cells Application

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ABSTRACT

The Fuel Cells is a renewable and clean energy power sources must be considered that can be used in a wide range of applications. But fuel cells cannot directly connected to load because fuel cells is a low output voltage. The fuel cells is connected to load by boost converter. This paper presents 4-phase fuel cell boost converter at a phase shift of 90 degree, with interleaved technique and parallel the power circuit, which enables to adapt the rated voltage (26V) to applications voltage (60V). By the principle of pulse width modulation (PWM) for driving power MOSFET and a constant switching frequency of 25kHz. The converter will operate at high efficiency and low ripple current. Experiment results with PEM fuel cells 1.2 kW, 26 V, 46 A. Verify that the 4-phase fuel cell boost converter by using interleaved switching technique controller have efficiency of 86 %.

Keywords: Fuel Cells, Boost converter, Interleaved technique

1. INTRODUCTION

Fuel cell [1],[2],[3] is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by-product. As long as fuel is supplied, the fuel cell will continue to generate power. Since the conversion of the fuel to energy takes place via an electrochemical process, not combustion, the process is clean, quiet and highly efficient two to three times more efficient than fuel burning. No other energy generation technology offers the combination of benefits that fuel cells do. In additional to low or zero emissions, benefits include high efficiency and reliability, multi-fuel capability, sitting flexibility, durability, scalability and ease of maintenance. Fuel cells operate silently, so they reduce noise pollution as well as air pollution and the waste heat from a fuel cell can be used to provide hot water or space heating for a home or office.

Fig. 1 shows the pressurized hydrogen gas (H_2) entering the fuel cell on the anode side. This gas is forced through the catalyst by the pressure. When an H_2 molecule comes in contact with the platinum on the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are conducted through the anode, where they make their way through the external circuit and return to the cathode side of the fuel cell. Meanwhile, on the cathode side of the fuel cell, oxygen gas is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H^+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O).

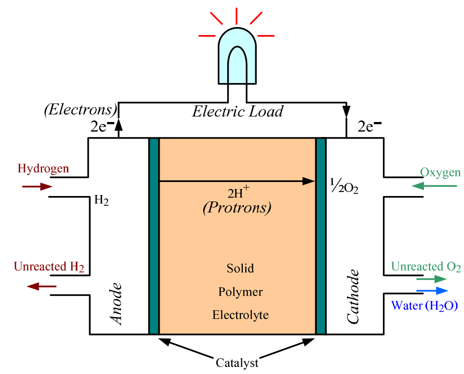

Fig. 1 Basic Elements of a PEMFC

2. FUEL CELL BASIC PRINCIPLE

2.1 Proton Exchange Membrane fuel cell (PEMFC)[4]

Proton Exchange Membrane fuel cell (PEMFC). These fuel cells operate at relatively low temperatures (about 175 °F), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications, such as in automobiles, where quick startup is required. According to the U.S. Department of Energy (DOE), "they are the primary candidates for light-duty vehicles, for buildings, and potentially for much smaller applications such as replacements for rechargeable batteries." This type of fuel cell is sensitive to fuel impurities. Cell outputs generally range from 50 watts to 75 kW.

There are four basic elements of a PEM fuel cell:

The **Anode**, the negative post of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst. One can write a chemical reaction at anode side as,

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

The **Cathode**, the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water. One can write a chemical reaction at cathode side as,

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

Combining the anode and cathode reactions, the overall cell reactions is,

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

The **Electrolyte** is the proton exchange membrane. This specially treated material, which looks something like ordinary kitchen plastic wrap, only conducts positively charged ions. The membrane blocks electrons. For a PEMFC, the membrane must be hydrated in order to function and remain stable.

The **Catalyst** is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum nanoparticles very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the PEM.

Electrons, which appear on the anode side, cannot cross the membrane and are used in the external circuit before returning to the cathode. Proton flow is directly linked to the current density:

$$J_{H^+} = \frac{i}{F} \tag{4}$$

Where F is the Faraday's constant.

The value of the output voltage of the cell is given by Gibb's free energy ΔG and is:

$$V_{rev} = -\frac{\Delta G}{2F} = 1.23V \tag{5}$$

This theoretical value is never reached even at no load. For the rated current (around 0.5 A.cm^{-2}), This reaction in a single fuel cell produces only about 0.7 volts. To get this voltage up to a reasonable level, many separate fuel cells must be combined to form a fuel cell stack. Then a fuel cell is always an assembly of elementary cells which constitute a stack as shown in Fig. 2

The Fig. 2 shows the PEMFC which is used for this research. Constructed by the Heliocentris Energiesysteme GmbH, the fuel cell stack is composed of 47 cells, "Heliocentris and Ballard Power System" Nexa® Power Module 1.2 kW, 26 V, 46 A.

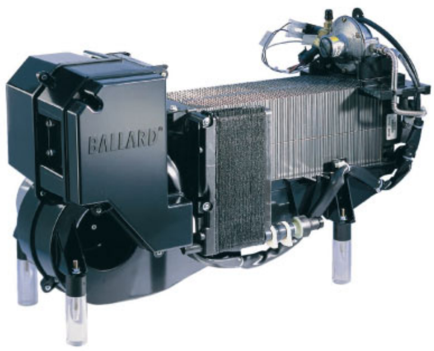

Fig. 2 PEMFC stack (47 cells)

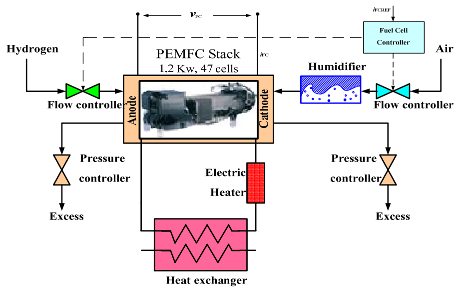

Fig. 3 Diagram of a 1.2 kW PEM Fuel cell

2.2 Fuel Cell System

The Fig. 3 shows the diagram of the PEMFC which is used for this research.

3. FUEL CELL CONVERTER

3.1 Boost Converter [6]

The boost converter, also known as the step-up converter, the boost converter functions to adapt the fuel cell voltage ($26V_{DC}$) to the application voltage (60 V_{DC}) the basic circuit of the boost converter is shown in Fig. 4

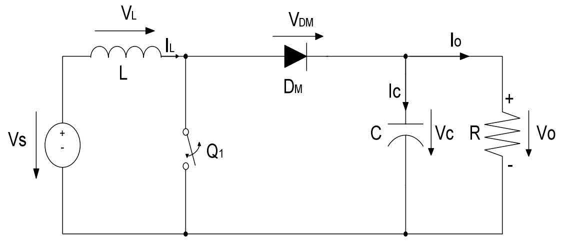

Fig. 4 The Basic Schematic of a Boost Converter.

The operation of the circuit is explained now. The essential control mechanism of the circuit in Fig. 4 is turning the power semiconductor switch on and off. When the switch is ON, the current through the inductor increases and the energy stored in the inductor builds up. When the switch is off, current through the inductor continues to flow via the diode D, the RC network and back to the source. The inductor is discharging its energy and the polarity of inductor voltage is such that its terminal connected to the diode is positive with respect to its other terminal connected to the source. It can be seen then the capacitor voltage has to be higher than the source voltage and hence this converter is known as the boost converter. It can be seen that the inductor acts like a pump, receiving energy when the switch is closed and transferring it to the RC network when the switch is open.

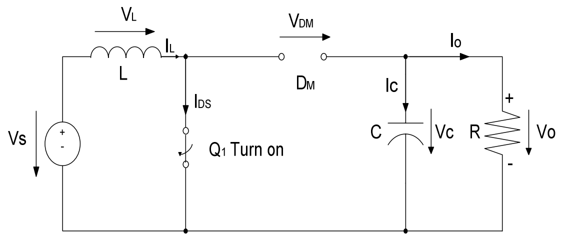

Fig. 5 Switch Closed State

When the switch is closed, the diode does not conduct and the capacitor sustains the output voltage. The circuit can be split into two parts, as shown in Fig. 5 As long as the RC time constant is very much larger than the on-period of the switch, the output voltage would remain more or less constant.

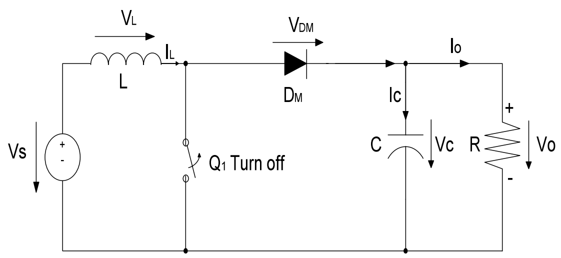

Fig. 6 Switch Open State

When the switch is open, the equivalent circuit that is applicable is shown in Fig. 6 there is a single connected circuit in this case.

3.2 4-Phase Boost Converter

The boost converter to generate output voltages of 60 V from fuel cell voltage [5]. In these high power applications and above, large inductor *L*, output capacitor, and diodes are required. When splitting the power stage into 4-phase boost converter reduces stress on the power components and easy installation.

$$i_{FC} = i_{L1} + i_{L2} + i_{L3} + i_{L4} \tag{6}$$

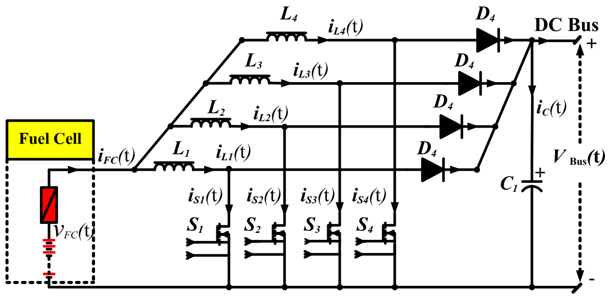

Fig. 7 4-Phase Boost Converter Circuit

3.3 Power Circuit Design

The 4-phase boost converter has the following specifications: rate input voltage and current 26 V, 40 A, output voltage 60 V, and switching frequency (Fs) = 25 kHz. Assuming an efficiency (η) of 90 % of the boost converter, then:

$$P_{in} = V_{in} \cdot I_{in} \tag{7}$$

$$P_{out} = P_{in} \cdot \eta \tag{8}$$

$$I_{out} = P_{out} / V_{out} \tag{9}$$

We can obtain the maximum duty cycle (*D*), is:

$$D = 1 - \left(V_{in} / V_{out}\right) \tag{10}$$

At the maximum duty cycle, the rms current rating $I_{S,rms}$ of the switches is:

$$I_{S,rms} = I_{in}\sqrt{D} \tag{11}$$

The reverse blocking voltage is equal to the DC bus voltage 60 V for power diode. Diode D can be rated for 60V The rms current, $I_{D,rms}$, through the diode, is given by:

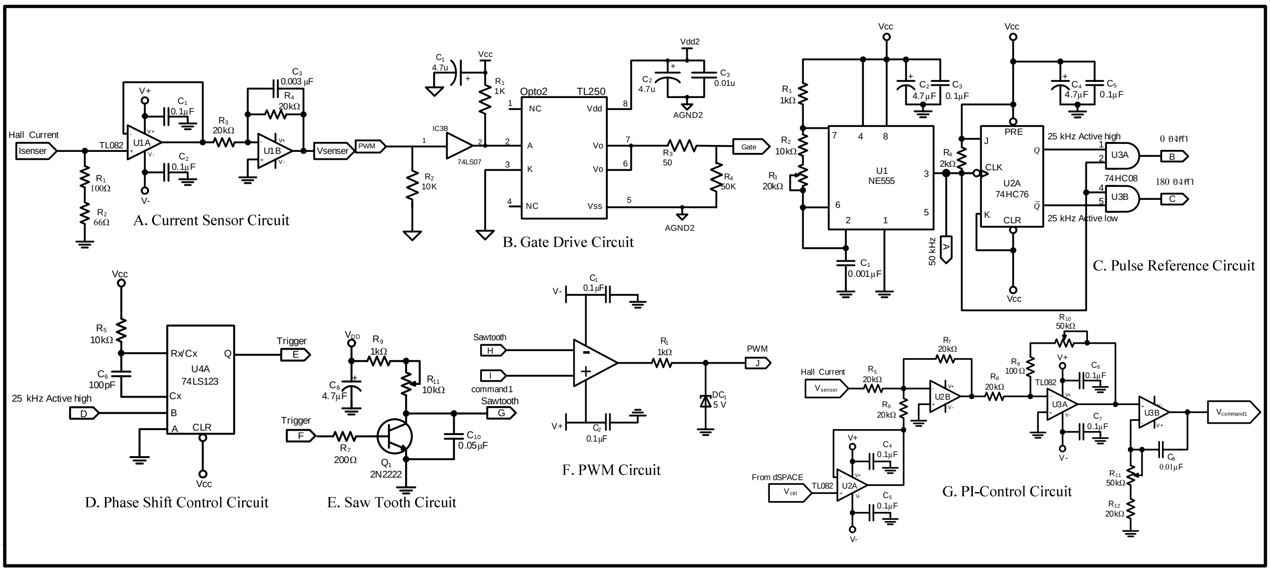

Fig. 8 4-Phase Converter Switching Control Unit

$$I_{D,rms} = I_{in}\sqrt{1-D} \quad (12)$$

Selecting a proper output capacitor (C) contributes to the reduction in output voltage ripple. The rms capacitor current, $I_{C,rms}$ is:

$$I_{C,rms} = \sqrt{I_{D,rms}^2 - I_{out,rms}^2} \quad (13)$$

These are bulk capacitors and the ripple voltage across it is assumed to be 1%

$$C = \frac{I_{out} \cdot D}{\Delta V_{out} \cdot f} \quad (14)$$

The input filter current, ripple and peak, determine the size of the inductor L. The input ripple current is assumed to be 12 % of rated current. The inductors sized as follows:

$$L = \frac{V_{in} \cdot D}{\Delta I_L \cdot f} \quad (15)$$

Experimental identification of parameter (7)-(15) leads to table 1.

Table 1 The Components Parameters.

Description	*Specify*
Duty Cycle (D)	0.57
C_{Bus}	681.8 μF
Inductor L_1, L_2, L_3, L_4	214.8 μH
Power Semiconductor Switch S_1, S_2, S_3, S_4	MOSFET IRFP264N (250 V, 38 A)
Diode D_1, D_2, D_3, D_4	RuRG3020 (200 V, 30A)
Switching Phase Shift	90 ˚

3.4 Switching Gate Control

In the Fig. 8 is 4-phase converter switch control unit. But in this present cannot show design and detail. We willed show in the next time.

3.5 Control Structure

The control structure of the PEMFC 4-phase converter is shown in Fig. 9 Current control is a close loop control. Induction current (i_{LMea}) adapt to voltage by buffer circuit. After that is to first order filter for high frequency switching harmonics decrease, and to a summing unit for error data. Finally error data is to PI-control for saw-tooth referent. Thus this signal is PWM (difference T_{on}). The operation function other phase is same, but a phase shift of 90 degree.

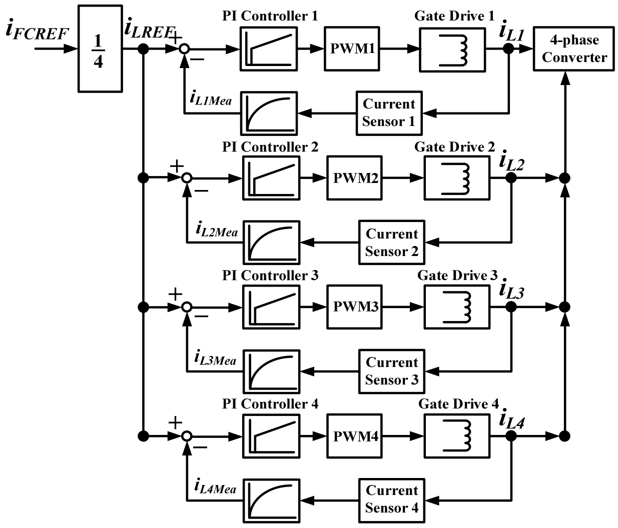

Fig. 9 4-Phase Converter Control Structure

4. EXPERIMENTAL RESULTS

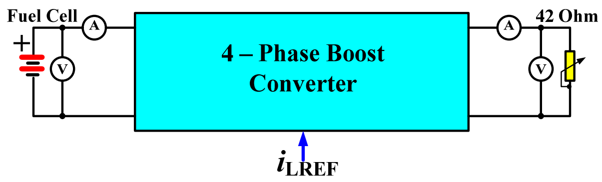

Fig. 10 Simplified Diagram Test Bench

Experimental results with a PEMFC "Heliocentris and Ballard Power System" Nexa® Power Module by Heliocentris Energiesysteme GmbH, Module 1.2 kW, 26 V, 46 A (47 cells), rail-time control, numerical calculation in dSPACE DS1104, The Control Desk software enables changes in the parameters of the control loops, and high power resistance 42 Ω is a test load.

Table 2 Test Bench Response Data

i_{LRef} (A)	$i_{in}(i_{FC})$ (A)	$v_{in}(v_{FC})$ (V)	i_{Bus} (A)	v_{Bus} (V)	Efficiency (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

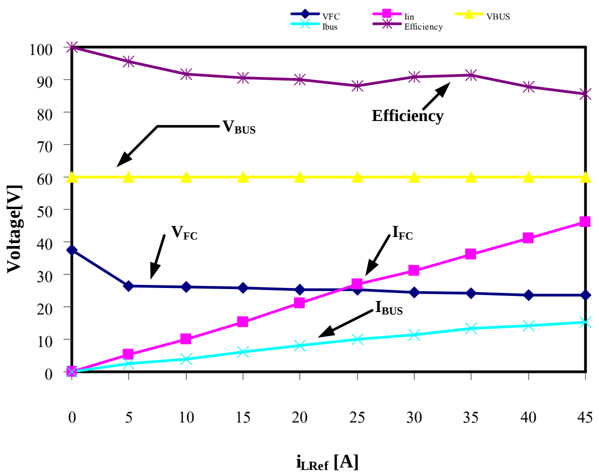

Fig. 11 4-Phase Boost Converter Response Test Bench

Table 2. shows results of 4-phase converter test bench. Fig. 11 shows the voltage and current (V_{FC}, I_{FC}, V_{Bus}, I_{Bus}) and system efficiency (η) response with a step current command (i_{LRef}) This results show that the regulation of the 4-phase boost converter correctly works.

5. CONCLUSION

In this paper the main objective of this work is to design, implement and test a 4-phase converter for PEMFC. Experiment results with PEM fuel cells 1.2 kW, 26 V, 46 A. Verify that the 4-phase fuel cell boost converter by using interleaved switching technique controller have efficiency of 85-95 % at 60 V output voltage.

The experimental results obtained with the 1.2 kW PEMFC confirm the relative slowness of this device, and one currently works associate a PEMFC with a auxiliary power source such as batteries in order to operate at high dynamics.

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