A DC – DC converter for PEMFC stack power conditioning applications

Makani Mwinga¹,4, Ben Groenewald¹ and Michael McPherson²,3

¹ Electrical, Electronic and Computer Engineering Department, Cape Peninsula University of Technology, Cape Town, P.O Box 1906 Bellville 7535 Republic of South Africa
² Director for Centre of Postgraduate Studies, Cape Peninsula University of Technology, Cape Town, P.O Box 1906 Bellville 7535 Republic of South Africa
³ Physics Department, Cape Peninsula University of Technology, Cape Town, P.O Box 1906 Bellville 7535 Republic of South Africa
⁴ E-mail: mwingamakani@yahoo.com

Abstract. Fuel cell technology is one of the most sought – after renewable technology. However, the output voltage of fuel cell (FC) stacks is inherently unstable, as such; it is of little or no use for most power supply applications. In addition to the unstable output voltage, FC stacks are susceptible to high current ripples, which can reduce the system’s life expectancy. It is therefore a requirement that the output voltage is stabilised and the high current ripple reduced in order to make FC technology useful. In order to achieve this, a power-conditioning unit (PCU) is interfaced directly to the FC stack module. The PCU is realised by means of a DC – DC converter or DC – AC inverter or a combination of both. This paper presents a PWM DC – DC Interleaved Boost Voltage Multiplier (IBVM) converter as the PCU for a Polymer Electrolyte Membrane Fuel Cell (PEMFC) stack. The mathematical modelling of the converter is validated by simulation in MATLAB/SIMULINK. Important simulation results are presented herein: which show that the output voltage of a PEMFC stack can be stabilised.

1. Introduction
Of the currently existing renewable energy technologies, fuel cell (FC) technology is considered to be one of the better options due to its cleanliness, its modularity, its high efficiency and its non-intermittence as compared to wind and solar energy sources [1]. According to Mushsin and Zehra [2], the use of FC technologies has been implemented over a wide spread of applications such as residential combined heat and power (CHP), transportation and industrial to name but a few. In 2014, Anglo America and Ballard launched a pilot project for rural electrification using Polymer Electrolyte Membrane fuel cell (PEMFC) at Naledi Trust Community in South Africa, powering 34 households [3]. To this end, Sammes and Boersma [4] alludes that a fair amount of research has been carried out on the subject of FC technology.

A FC is an electrochemical device designed to generate a voltage through a chemical reaction, with heat and water produced as a by-product [5–8]. There are about six major types of fuel cells available on the market today [9, 10]. Generally, fuel cells are distinguished according to the chemical composition of the electrolyte and the fuel used [9, 11]. Several fuel cells piled together are referred to as a stack and individual voltages of each FC combine to form a FC stack voltage [11]. The problem is
that, the stack voltage is low and unstable; therefore, it is of little or no use for most power supply applications [12]. Another problem is that, as the stack voltage fluctuates, the individual FC voltage falls significantly as the current density rises; this generates unwanted current ripple within the stack, which can reduce the life expectancy of the stack [3, 13]. Therefore, it is then a requirement to boost and stabilise the stack voltage and to reduce the stack current ripple.

An appropriate power-conditioning unit (PCU) is required in order to boost and stabilise the stack voltage and to reduce the stack current ripple [14]. A PCU can be realised by means of a DC – DC converter topology or a DC – AC inverter topology or a combination of both [15]. The PCU converts the stack voltage to a higher and stabilised voltage, and it is directly interfaced to the FC stack module [16]. Various converter and inverter topologies used in PCUs for PEMFC stacks and their technicalities are discussed in [17–22]. Based on the literature review, the Interleaved Boost Voltage Multiplier (IBVM) converter was adopted for the design of the PCU for a 1 kW Horizon PEMFC. The IBVM converter presented herein is based on the work of [23, 24].

2. Polymer electrolyte membrane fuel cell (PEMFC)

The performance characteristic of a FC stack is described by the polarisation curve of the individual FCs that make up a FC stack [25]. Figure 1 shows the polarisation curve of voltage versus current for a single fuel cell. The curve consists of three regions: rapid initial fall in voltage due to activation losses, fairly linear region due to ohmic losses and faster fall in voltage at higher currents due to concentration losses. As shown by the curve, the FC stack output voltage is low and unstable. Therefore, for any practical applications, the FC stack voltage must be regulated at a desired value.

A power conditioning unit (PCU) is used to perform the required and necessary voltage regulation, voltage boost and often voltage inversion of the FC stack voltage. The PCU consists of a converter or an inverter or a combination of both. Herein, a DC – DC interleaved boost voltage multiplier (IBVM) converter is used to regulate and boost the voltage of a PEMFC. The PEMFC stack has the following specifications: 36 V – 67 V voltage range, 0 A – 30 A current range and 0 kW – 1.2 kW electrical power range.

![Figure 1. The polarisation curve[15].](image)

3. Interleaved boost voltage multiplier (IBVM) converter

Figure 2(a) shows the steady state voltage and current switching waveforms, figure 2(b) shows the circuit topology and figure 2(c) – 2(f) show the converter circuits during different converter operating modes over one switching cycle, $T_S$. The converter circuit topology consists of: an input voltage $V_i$, inductors $L_1$ and $L_2$, switches $S_1$ and $S_2$, switching diodes $D_1$ – $D_4$, energy transfer capacitor $C_1$, output filter capacitors $C_2$ and $C_3$, load resistor $R$ and an output voltage $V_O$. In figure 2(a), $V_{GS1}$ and $V_{GS2}$ are
gate to source voltage signals of the switches, $i_{L1}(t)$ and $i_{L2}(t)$ are inductor instantaneous currents, $i_{DS}(t)$ and $i_{DS2}(t)$ are diode instantaneous currents, $V_{C1}(t)$ – $V_{C2}(t)$ are capacitor instantaneous currents.

Figure 2. IBVM converter: (a) Steady state voltage and current switching waveforms. (b) Converter circuit topology. (c) Converter circuit during mode 1. (d) Converter circuit during mode 2. (e) Converter circuit during mode 3. (f) Converter circuit during mode 4.

3.1. Converter operation
In the analysis of the IBVM circuit topology, it is assumed the converter is operating under steady state conditions, with continuous current mode (CCM). Under such conditions, the operation of the converter over one switching cycle, is divided into four operating modes as shown by figure 2(a). The interval $t_0 – t_4$ is equal to one switching cycle, $T_s$. The switches are hard switched and are operated by gate signals that are 180° phase shifted in order to warrant a switch overlap.

Figure 2(c) shows the equivalent circuit of the converter during mode 1. This mode corresponds to the time interval $t_0 – t_1$. Both switches turn on and conduct the input current $I_L$. All diodes are reverse biased except $D_3$ and the inductors are charged up by the source. If $V_{C1}$ is lower than $V_{C3}$, $D_3$ is
forward biased, allowing $C_3$ to discharge current into $C_1$ until $V_{C1}$ is clamped to $V_{C3}$. This action allows the voltage in all capacitors to be clamped to the same level over one $T_S$. The output voltage, $V_O$, is equal to the sum of the voltages across $C_2$ and $C_3$.

Figure 2(d) shows the equivalent circuit of the converter during mode 2. This mode corresponds to the time interval $t_1 - t_2$. $S_1$ turns off, $D_2$ and $D_4$ are reverse biased while $D_1$ and $D_3$ are forward biased. $L_1$ discharges current into $C_3$, while $L_2$ is charged up by the source. $V_O$ is equal to the sum of the voltage across $C_2$ and $C_3$.

Figure 2(e) shows the equivalent circuit of the converter during mode 3. This mode corresponds to the time interval $t_3 - t_4$. $S_2$ turns off, $D_1$ and $D_3$ are reverse biased while $D_2$ and $D_4$ are forward biased. $L_1$ is charged up from the source, while $L_2$ discharges current into $C_3$.

3.2. Converter mathematical modelling

The equations that describe the dynamics of the converter voltage and current over one switching cycle are derived by applying the circuit averaging technique to the voltage and current waveforms of the converter over one switching cycle. A thorough derivation of the converter dynamic equations is covered in [26]. Of interest are the average inductor voltages: $\langle V_{L1}(t) \rangle$ and $\langle V_{L2}(t) \rangle$; average capacitor currents: $\langle i_{C1}(t) \rangle$, $\langle i_{C2}(t) \rangle$ and $\langle i_{C3}(t) \rangle$; average output equivalent capacitor current $\langle i_{Ceq}(t) \rangle$; inductor current ripple: $\Delta i_{L1}$ and $\Delta i_{L2}$; capacitor voltage ripple: $\Delta V_C$; output voltage: $V_O$; converter DC transfer function: $M(D)$ and converter DC current transfer function: $M(I)$. These are given as

$$\langle V_{L1}(t) \rangle = \frac{1}{T_S} \int_0^{T_S} v_{L1}(t) dt = V_l - \frac{V_O D'}{2}, \quad (1)$$

$$\langle V_{L2}(t) \rangle = \frac{1}{T_S} \int_0^{T_S} v_{L2}(t) dt = V_l - \frac{V_O D'}{2}, \quad (2)$$

$$\langle i_{C1}(t) \rangle = \frac{1}{T_S} \int_0^{T_S} i_{C1}(t) dt = -I_{L2} D + \frac{V_O}{R}, \quad (3)$$

$$\langle i_{C2}(t) \rangle = \frac{1}{T_S} \int_0^{T_S} i_{C2}(t) dt = -\frac{V_O}{R} - C_1 \frac{d V_{C1}(t)}{dt} D', \quad (4)$$

$$\langle i_{C3}(t) \rangle = \frac{1}{T_S} \int_0^{T_S} i_{C3}(t) dt = C_2 \frac{d V_{C2}(t)}{dt} - C_1 \frac{d V_{C1}(t)}{dt} D + \left( I_{L1} + I_{L2} - \frac{V_O}{R D'} \right) D', \quad (5)$$

$$\langle i_{C_{eq}}(t) \rangle = \frac{1}{T_S} \int_0^{T_S} i_{C_{eq}}(t) dt = I_l D' - \frac{2 V_O}{R}, \quad (6)$$

$$\Delta i_{L1} = \frac{V_O \left(D^2 R\right) D}{2D'RL_l T_S}, \quad (7)$$

$$\Delta i_{L2} = \frac{V_O \left(DD^2 R\right)}{2D'RL_l T_S}. \quad (8)$$

$$\Delta V_C = \frac{V_O D}{2CRl}, \quad (9)$$
\[ V_0 = \frac{2V_{IN}}{D'} \]  
\[ M(D) = \frac{V_0}{V_i} = \frac{2}{D'} \]  
\[ M(I) = \frac{I_O}{I_i} = \frac{D'}{2} \]  

3.3. Converter design

Table 1 shows the converter design specifications. As previously discussed, the PEMFC generates a low and unstable output voltage that must be boosted, regulated and often inverted to a standard 230/240 VAC at 50/60 Hz for any practical applications. In this work, a DC – DC IBVM converter was the preferred option for the PEMFC stack PCU. The function of the converter is to regulate and boost the 36 VDC – 67 VDC output of the FC stack to 200 VDC.

| Parameter          | Value                  |
|-------------------|------------------------|
| Input voltage (V_i) range | 36 VDC – 67 VDC |
| Output voltage (V_o)      | 200 VDC               |
| Switching frequency (f_s)    | 50 kHz                |
| Input current ripple (\(\Delta I_i\)) | 0.3 I_i            |
| Output voltage ripple (\(\Delta V_o\)) | < 0.1 V_o          |
| Desired converter efficiency | 0.9                 |

Table 2 shows the component list of the IBVM converter power stage design. The component values were determined by using the converter design specifications, parameter and component equations derived in the modelling section.

| Parameter          | Value                  |
|-------------------|------------------------|
| C_1, C_2 and C_3  | 244.82 \(\mu\)F       |
| L_1 and L_2       | 288 \(\mu\)H and 287.31 \(\mu\)H |
| R                 | 44.44 \(\Omega\) – 400 \(\Omega\) |
| D                 | 0.4 – 0.68             |

4. Simulation results

Simulation results for the Simulink model of the FC stack and the IBVM converter are presented in this section.

MATLAB/Simulink 2014a student version software was used for simulation of the IBVM converter model. Figure 3 shows the Simulink model of the FC stack and the IBVM converter. The FC stack block supplies power to the IBVM converter model. While the controller and feedback network block senses \(V_o\) and generates the control voltage, which controls the duty cycle of the switches,
thereby regulating $V_O$. The variable load sinks current from the converter proportional to the present ratio of $V_O/R$.

Figure 3. The Simulink model of the FC stack and IBVM converter.

Figure 4 shows some of the waveforms for the output voltage and output current of the converter and FC stack, in response to loads transients, over 0.5 s. $I_{L1}$, $I_{L2}$, $V_O$, $I_O$, $V_{FC}$ and $I_{FC}$ stabilise at 75 ms after start-up. At 0.25 s a load transient is introduced, hence: $V_{FC}$ increases slightly and develops moderate ripples, $I_{FC}$ decreases and develops high ripple content, $V_O$ remains stable at 200 V, $I_O$ decreases, $I_{L1}$ and $I_{L2}$ decrease and develop high ripple content. At 0.45, another load transient is introduced, hence: $V_{FC}$ increases slightly, $I_{FC}$ decreases slightly and its ripple also reduces slightly, $V_O$
remains stable at 200 V, $I_0$ decreases further, $I_{L1}$ and $I_{L2}$ decrease further and their ripple content also reduce slightly.

The results indicate that $V_N$ stabilises at 200 V regardless of load transients. This is proof that the fuel cell stack output voltage, $V_{FC}$, is regulated and boosted to 200 V and that the modelling of the converter is valid.

5. Conclusions

FC technology is one of the promising existing renewable energy technologies. However, the low and unstable output voltage of FC stacks, associated with high current ripples, make FC technology unpractical for most power supply applications. In order to make FC technology practical for power supply applications, the output voltage of a FC stack must be boosted and stabilised, and the FC stack current ripples reduced. This can be achieved by using a power conditioning unit (PCU). This paper has presented a DC – DC interleaved boost voltage multiplier (IBVM) converter, as the PCU for PEMFC stack power applications. The DC transfer function, the dynamic and parameter equations of the converter were derived in the mathematical modelling section. The values of the parameters and components for the converter were calculated by using the derived component and parameter equations.

A Simulink simulation model consisting of a FC stack and IBVM converter was developed for the performance analysis of a 1 kW PEMFC stack power supply unit. The obtained simulations results indicate that the FC stack output voltage was regulated and boosted. The results also indicate that the stack current ripple and voltage ripple were reduced. Further, the results indicate that the IBVM converter offers high DC voltage gain, low stack current ripples and low stack voltage ripples.

The future research work needs to consider experimental verification of the mathematical modelling, design and simulation results of the IBVM converter.

References

[1] Vazquez-Blanco A, Aguilar-Castillo C, Canales-Abarca F, and Arau-Roffiel J 2009 Two-stage and integrated fuel cell power conditioner: Performance comparison Proc. Conf. on IEEE Applied Power Electronics and Exposition 452–458
[2] Gencoglu M T and Ural Z 2009 Design of a PEM fuel cell system for residential application J. International. Hydrogen Energy 12 5242–5248
[3] Gmbh D A 2015 Fuel cell technology providing power to South African schools Fuel Cells Bulletin 7 5–6
[4] Sammes N M and Boersma R 2000 Small-scale fuel cells for residential applications J. Power Sources 1 98–110
[5] Farooque M and Maru H C 2001 Fuel Cells — The Clean and Efficient Power Generators J. Proceedings of the IEEE 12 1819–1829
[6] Stambouli A B and Traversa E 2002 Fuel cells an alternative to standard sources of energy J. Renewable Sustainable Energy Reviews 3 295–304
[7] Wang C and Nehrir M H 2006 Distributed Generation Applications of Fuel Cells Proc. Conf. on Power Systems: Advanced Metering, Protection, Control, Communication, and Distributed Resources 244–248
[8] Rey A F, Eduardo Ortiz-Rivera I and Angel Reyes-Hernandez L 2007 Understanding the history of fuel cells Proc. Conf. on IEEE History of Electric Power 117–122
[9] Kirubakaran A, Jain S, and Nema R K 2009 A review on fuel cell technologies and power electronic interface J. Renewable Sustainable Energy Reviews 9 2430–2440
[10] Abd El Monem A A, Azmy A M, and Mahmoud S A 2014 Effect of process parameters on the dynamic behavior of polymer electrolyte membrane fuel cells for electric vehicle applications J. Ain Shams Engineering 1 75–84
[11] Penner S S Ucsd et al 1995 Commercialization of Fuel Cells J. Progress Energy Combustion Science 2 145–151
[12] Mwinga M, Groenewald B and McPherson M 2015 Design, Modelling and Simulation of a Fuel Cell Power Conditioning System J. Thermal Engineering 3 408–419
[13] Hua C, Huang C and Chiu H 2007 Research on Dynamic Response of Hybrid Power Source Systems with PEMFCs and Lead-Acid Batteries Proc. Conf. on Power Conversion 739–744
[14] EG and G Technical Services 2004 Fuel Cell Handbook edition 7th, ed Mark C. Williams
[15] Larminie L and Dicks A 2003 Fuel cell systems explained edition 2nd, ed John Wiley & Sons
[16] Vazquez A, Aguilar C, Canales F and Ponce M 2008 Integrated power conditioner topology for fuel cell based power supply systems Proc. Conf. on IEEE Power Electronics Specialists 223–229
[17] Zhang S and Yu X 2012 Design Considerations of the Interleaved Boost Converter in Photovoltaic/Fuel Cell Power Conditioning System Proc. Int. Conf. on IEEE Telecommunications Energy
[18] Andersen G K, Klumpner C, Kjaer S B, and Blaabjerg F 2002 A new green power inverter for fuel cells Proc. Int. Conf. on 33rd Annual IEEE Power Electronics Specialists 727–733
[19] Palma L 2012 DC/DC converter topology selection for low frequency ripple reduction in PEM fuel cell applications Proc. Int. Conf. on Power Electronics, Electrical Drives, Automation and Motion 315–319
[20] Palma L 2013 Current source converter topology selection for low frequency ripple current reduction in PEM fuel cell applications Proc. Conf. on 39th Annual IEEE Industrial Electronics Society 1577–1582
[21] Miranda U A, Bellar M D, Da Silva Neto J L and Aredes M 2006 Evaluation of reduced component count converters for low harmonic distortion AC drive systems Proc. Int. Conf. on IEEE Symposium on Industrial Electronics 2504–2509
[22] Jain S, Jiang J, Huang X and Stevandic S 2012 Modeling of fuel-cell-based power supply system for grid interface J. IEEE Transactions on Industry Applications 4 1142–1153
[23] Rosas-Caro J C, Mayo-Maldonado J C, Salas-Cabrera R, Gonzalez-Rodriguez A, Salas-Cabrera E N and Castillo-Ibarra R 2011 A family of DC-DC multiplier converters J. Engineering Letters 1 21–27
[24] Rahavi J S A, Kanagapriya T and Seyezhai R 2012 Design and analysis of Interleaved Boost Converter for renewable energy source Proc. Int. Conf. on Computing, Electronics and Electrical Technologies 447–451
[25] Farooque M and Maru H C 2001 Fuel cells-the clean and efficient power generators J. Proc. IEEE 12 1819–1829
[26] Mwinga M 2017 Design and development of a Fuel Cell Power Supply unit [D] Cape Peninsula University of Technology