

Modelling and Simulation of Proton Exchange Membrane Fuel Cell for Stand-Alone System



Rajesh Singla

Abstract Fuel cell system is an unconventional energy source that can be used in various stand-alone applications. The fuel cell gives an unstabilized voltage that is exclusively unacceptable for segregated applications. The primary objective of this study is to design an appropriate power conditioning unit that comprises of DC-DC converter stages along with DC-AC inverter. The capacitance and resistance are dependent on the proton exchange membrane fuel cell and cause electrical effects due to the behavioral changes of the output voltage of the fuel cell stack. This article discusses the electrical parameters of dynamic model of proton exchange membrane fuel cell. Its dynamic model was related to the boost converter-averaged dynamic model that is obtained by using the mathematical model of the boost converter circuit. This circuit keeps the output voltage of the converter constant and is being fed into the inverter to rectify the voltage, and a filter is also used to eliminate harmonics in the AC signal.

Keywords Proton exchange membrane fuel cell · Electrochemical impedance spectroscopy · DC-to-AC inverter · DC-to-DC converter · Filter and PWM

1 Introduction

Many traditional methods for the production of electricity such as burning fossil fuels were used for last many decades despite having various kinds of destructive environmental impacts. For instance, such methods increased the global warming with the rise in emission of greenhouse gases [1, 2]. Such factors make fuel cell (FC) technology a satisfactory choice for various external utilization.

Polymer exchange membrane fuel cell (PEMFC) is a type of fuel cell (FC), which proves its supremacy over other types of fuel cells in terms of characteristics like high power density, low temperature, and fast response. Despite this, factors like

R. Singla (✉)

Dr. B. R. Ambedkar NIT Jalandhar, Jalandhar, India
e-mail: rksingla1975@gmail.com

tremendous cost, limited lifespan, and awful authenticity of PEMFCs have limited the extensive applications of FC in real-time world [3, 4]. The most prominent drawbacks of FCs include load current imbalance and maximal load swings which further sometimes become the reason for voltage swings and power issues. Such issue is resolved by using proper power conditioning unit (PCU). The PCU is required to process the unprocessed power output of FCs so that it becomes utilizable.

DC-to-DC converters are used whenever an averaged voltage is needed as the output. Inverter is extensively used for backup generation of electricity for analytical loads like computers in various offices, life support systems in hospitals, power-houses, and also in transportation workstations, and communications systems [5]. This study focuses on modelling an isolated application where a PEMFC is considered as a basic energy source.

The output voltage of PEMFC is in a fluctuating DC form with the variations in the load. The prime and fluctuating 48 V DC input source models FC, and the boost DC-to-DC converter regulates the output of the PEMFC to 72 V.

The ideal standard potential of a PEMFC is 1.229 V (25 °C and 1 atm) with liquid water product. The permanent voltage losses happening in the FCs decrease the actual FC potential from the equilibrium point.

2 Losses in Fuel Cell

FC losses are credited to following grades: (i) activation overvoltage, (ii) ohmic overvoltage, and (iii) concentration overvoltage [3].

2.1 Activation Overvoltage

The activation overvoltage is the result of electron transfer need and breaking-forming of chemical bonds at anode as well as cathode. The activation overvoltage happens on both anode and cathode of the FC.

The hydrogen oxidation reaction at the anode is too fast, whereas oxygen reduction process at the cathode is significantly steady in speed [6]. There hence, potential loss because of the loss of activation is overcome by the cathode reaction.

2.2 Ohmic Overvoltage

The ohmic overvoltage is because of the polymer membrane resistance offered to the protons transfer and the resistance of both the electrodes: cathode and anode along with collecting plate offered to electron transfer [6, 9].

2.3 Concentration Overvoltage

The concentration overvoltage emerges as a result of concentration changes in the reactants because of their consumption during the reaction. Such losses lead to instant potential drop at greater currents [6, 7, 9].

3 Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy is a very useful technique in the characterization of the behavior of electrochemical cells. The data obtained from this model can be fitted to an electric circuit model that mimics chemical processes or models [10].

4 Cell Terminal Voltage

From the combination of all the voltage drops related to all losses mentioned above, the operating voltage of the FC is represented as follows:

$$V_{fc} = E - V_{act} - V_{ohm} - V_{conc} \quad (4.1)$$

where E is the open circuit potential E . The calculated potential V_{fc} shows potential of a single FC [5, 7–9]. Total stack voltage is calculated from the product of single cell voltage and the total number of cell in stack.

$$V_{st} = n \times V_{fc} \quad (4.2)$$

5 PEM Fuel Cell Electrical Circuit Model

Electrical circuit model consists of the membrane cell resistance R_m in series with a parallel combination of double-layer capacitance C_{dl} representing the membrane electrode interface and an impedance of faradic reaction consisting of charge transfer resistance R_{ct} and specific electrochemical element of diffusion Z_w as shown in Fig. 1 [10].

The characteristics of the above circuit when 40 cells are stacked together are shown in Fig. 2. It draws 1.11 A current when the values of C_1 and C_2 are considered negligible. The output voltage of the fuel cell is unregulated with change in the load (current) voltage, so we need a power converter circuit to correct this problem.

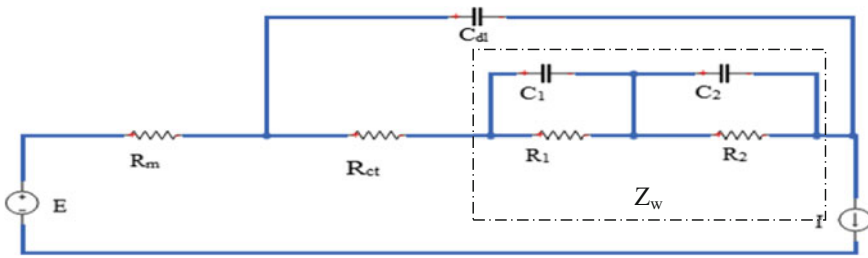


Fig. 1 Circuit of PEMFC

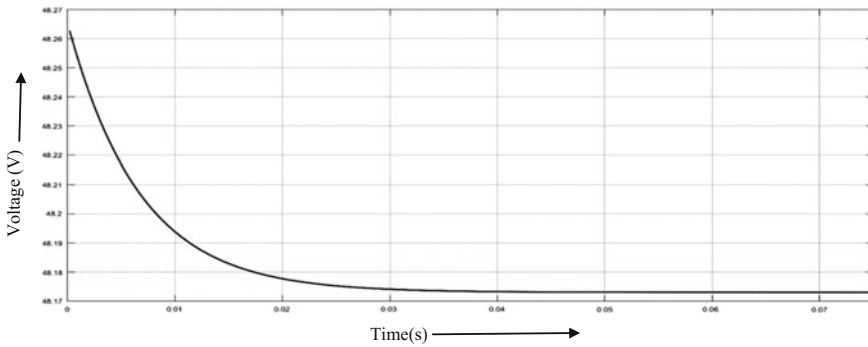


Fig. 2 Voltage drops across fuel cell

6 Power Conditioning Unit

This unit of power conditioning transforms the raw energy into utilizable energy for various applications.

While the DC output voltage in the fuel cell is not regulated, its updating is required for practical application. The power conditioning unit maintains the harmonics at an acceptable level. The conditioning system converts the gross energy into usable energy for all applications.

The FC output is an unregulated DC voltage that gets transformed to DC voltage administered by boost converter. The potential procured post filtration gets fed to DC-to-AC inverter. As per the load, the PCU will be brought into use to take out the needed current from the FC. The load current will be an explicit wave and will depend on frequency, the size of the inductor and the capacitor. Other than this, the inverter interfaces the FC from the grid power system which is used to create a mesh with the help of voltage or current in a suitable phase, frequency, and magnitude. PCU structure along with DC-to-DC pulse converter and DC-to-AC inverter stage is depicted in Fig. 3. There are various transitional phases shown in Fig. 3 that constitute filters for dampening of current harmonics as well as undesired voltages at the DC-to-DC converter and the DC-to-AC inverter output [2, 4].

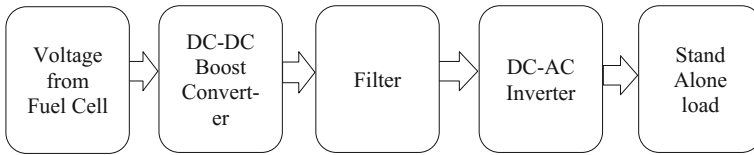


Fig. 3 Power conditioning blocks for PEMFC

6.1 The Levels of PCU

The FC output is a fluctuating DC voltage that gets varied along the variations in load. The boost converter is further transformed into a controlled DC voltage. Inverter acts as a network interface [2, 4].

6.2 DC-DC Boost Converter

As the load current increases, the FC voltage will be reduced, so the voltage of the unregulated terminals cannot be precisely linked to the DC bus. The DC-AC inverter cannot be used for stand-alone applications.

As a result, the FC stack is used in the linear work area for designing the converter (due to the strength of the internal components), as the use of the FC in nonlinear region damages the lamination.

Working of Boost Converter. When switch S is closed for time duration t_1 , the inductor current rises, and energy gets stored in the inductor. If the switch S is opened during time t_2 , the energy stored in the inductor is transferred to the load through the diode D, and the current of the inductor drops. When the switch S is open, the capacitor is charged by the voltage stored in the inductor. Therefore, the capacitor gets fully charged for use. The unsteady high-frequency switching voltage in the boost converter with 33% duty cycle becomes the required stable voltage [11, 12] (Figs. 4, 5, 6).

6.3 Designing of Boost Converter

A boost converter is designed to provide an output of 48 V from a 72 V source. The load is 80 W. The voltage and current ripple must be less than 0.5%. Specify the duty ratio, switching frequency, values, and ratings of each of the components. All the components used are assumed in their ideal states [11, 13, 14].

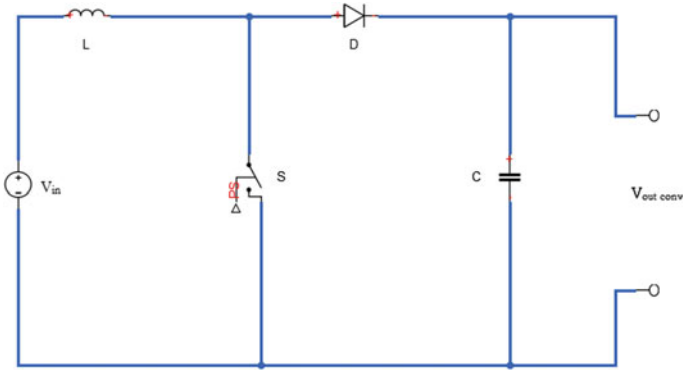


Fig. 4 Boost converter circuit

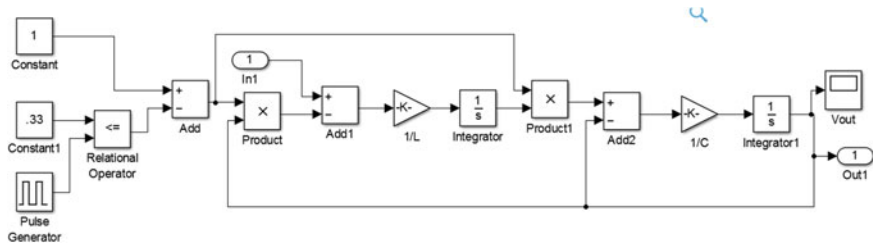


Fig. 5 Mathematical model of boost converter

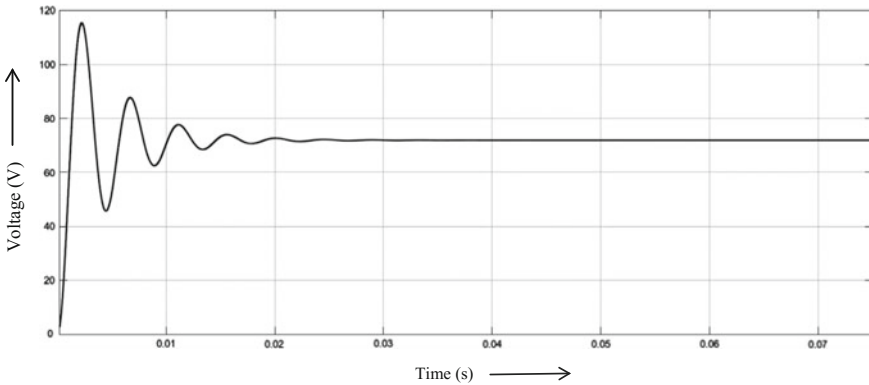


Fig. 6 Characteristic of boost converter

Given:

$$V_{in} = 48 \text{ V}$$

$$V_0 = 72 \text{ V}$$

$$\Delta V_0 \leq 0.5\% V_0$$

Design Assumptions:

- i. The switching frequency is assumed to be 25 kHz.
- ii. Inductor current is assumed to be continuous.

$$I_o = \frac{P}{V_0} = \frac{80}{72} = 1.11 \text{ A}$$

If D is the duty cycle of boost converter, then

$$\frac{V_0}{V_{in}} = \frac{1}{1-D};$$

$$D = 0.33$$

$$L_{min} = \frac{D(1-D)}{2f} R;$$

$$L_{min} = 48 \mu\text{H}$$

Let L = 150% of L_{min}

$$L = 1.5 * 48 = 72 \mu\text{H}$$

$$C \geq \frac{D}{R \frac{\Delta V}{V} f} R \geq 163 \mu\text{F}$$

$$\therefore C = 165 \mu\text{F}$$

7 Filter

The line filter reduces the high-frequency harmonic content of the line current that was caused by the switched operation of the voltage source inverter (VSI). Factors like filter cost, size, and application purpose are considered for the selection purpose [13].

LC filter can be used for minimization of harmonics at output side of the inverter.

7.1 Calculation of L and C

The inductive part of the low pass filter is designed on the basis of the allowable current ripple at switching frequency on the grid side [13, 14].

$$L = \frac{V_{DC}}{4 f_s \Delta i}$$

where VDC is the DC voltage, Δi is the value of the current ripple, and f_s is switching frequency.

For calculation of capacitor,

$$C = \frac{\Delta i}{8f_s \Delta V_0}$$

where ΔV_0 = voltage ripple.

8 PWM Generation

PWM techniques are identified by constant amplitude pulses. Their width is to be modulated for obtaining output voltage control along with reduction of its harmonic content [13]. Here, three different PWM techniques generally used are single pulse modulation, multiple pulse modulation, and sinusoidal pulse width modulation (carrier-based PWM technique). Here, the only carrier-based PWM technique is explained which is used in this paper.

8.1 Carrier-Based PWM

During this process, a triangular carrier wave gets compared to the reference sinusoidal voltage with the specified output frequency. When the reference signal is larger as compared to carrier signal, the upper switch gets on while the lower switch gets off, else the other way. Whenever reference signal is larger compared to carrier signal, the switching signal begins while it stops when carrier signal is larger compared to reference signal [13]. The functional value of switching signals seems sinusoidal where every pulse width is associated with amplitude of reference wave. The changes in amplitude of reference wave regulate output voltage of inverter. Mathematical model and characteristics of the PWM are shown in Fig. 7 and Fig. 8, respectively.

9 Single-Phase DC-to-AC Inverter

The inverters play a crucial role in converting DC to AC using electrical equipment like induction motor drive, uninterruptible power supply (UPS), and automatic voltage regulator (AVR). The basic aim to use the inverter is constructing a sinusoidal output voltage, which regardless of the kind of load creates stable and smooth waveform. Figure 9 shows the circuit diagram of the single-phase inverter. The single-phase complete bridge inverter comprises two identical arms consisting of four

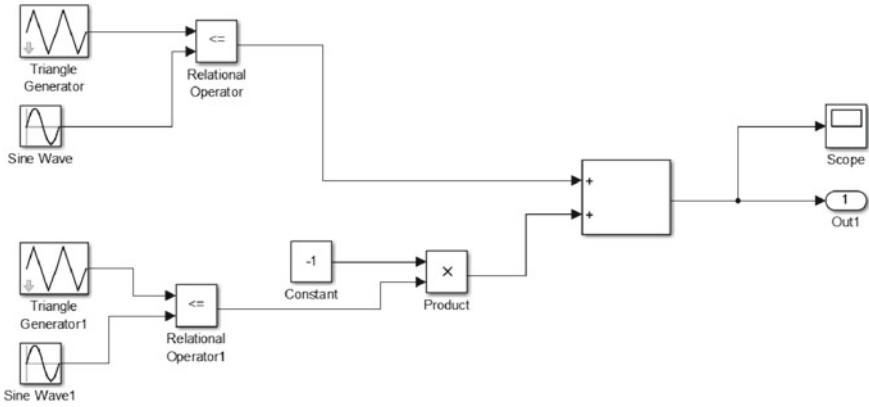


Fig. 7 Mathematical model of PWM

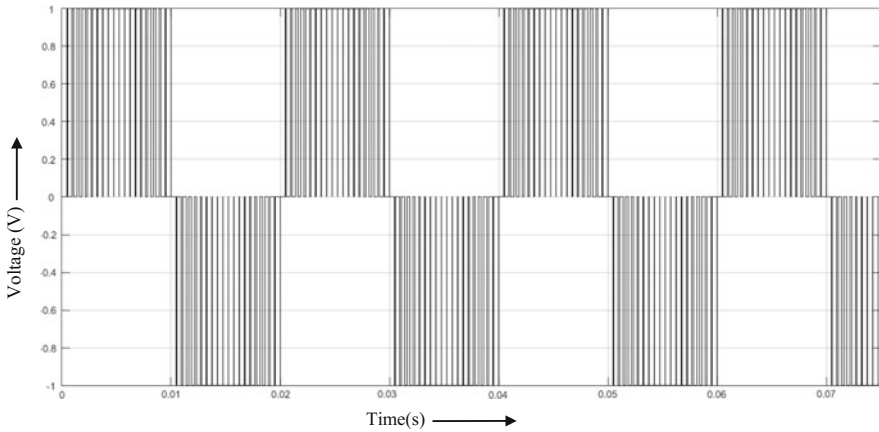


Fig. 8 PWM signal generator output

switches (S1, S2, S3, S4) along with four antiparallel diodes (D1, D2, D3, D4). On switching on S1 and S2, the output voltage becomes DC bus voltage +Vdc, and likewise on switching on S4 and S3, the output voltage becomes -Vdc [11, 12]. Figure 10 shows the mathematical model of DC-AC inverter. Figure 11 shows the sinusoidal output response of the DC-to-AC inverter.

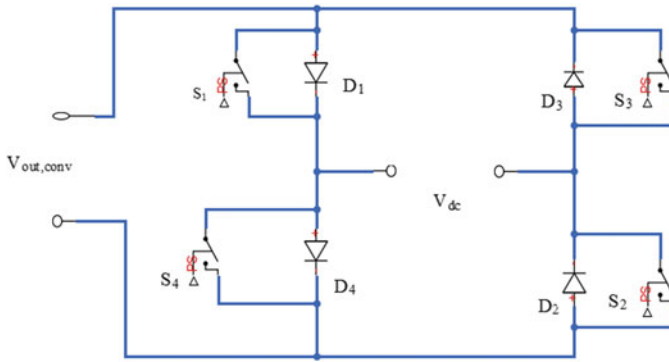


Fig. 9 DC-AC inverter circuit

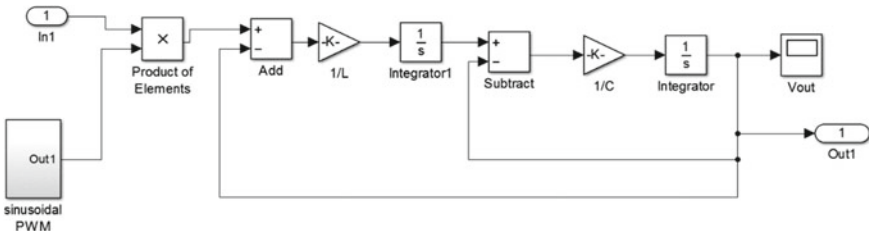


Fig. 10 Mathematical model of DC-AC inverter

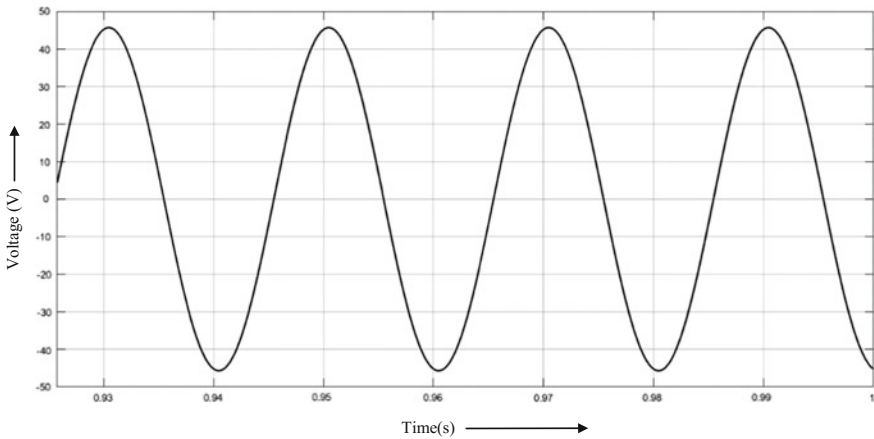


Fig. 11 Characteristic of inverter

10 Conclusion

This study presents a Simulink model for the PEMFC power system consisting of PEMFC stack, DC-to-DC converter, PWM-based DC-to-AC inverter. Modelling was done by adopting and deriving a mathematical model that explained the behavior of the fuel cell system. The PEMFC stack was modelled while counting the irreversibility. The performances of the fuel cells voltage are analyzed for a particular current range. Switching signals were input to the inverter model that were generated by the PWM.

References

1. Itoh, J.I., Hayashi, F.: Ripple current reduction of a fuel cell for a single-phase isolated converter using a DC active filter with a center tap. *IEEE Trans. Power Electron.*, 550–560 (2010)
2. Lee, S.H., Song, S.G., Park, S.J., Moon, C.J., Lee, M.H.: Grid connected photovoltaic system using current-source inverter. *Sol. Energy*, 411–419 (2008)
3. Larminie, J., Dicks, A.: *Fuel Cell Systems Explained*, 2nd edn. SAE International and Wiley Ltd, New York (2003)
4. Wang, C., Nehrir, M.H., Gao, H.: Control of PEM fuel cell distributed generation systems. *IEEE Trans. Energy Convers.* 586–595 (2006)
5. Liu, G., Liu, Y., Qi, Z.: Single-phase sinusoidal inverter based on fuzzy PID control for small wind power system. In: 2nd International Conference on Computer Science and Network Technology (ICCSNT), pp. 625–638 (2012)
6. Na, W.K., Gou, B.: Feedback-linearization-based nonlinear control for PEM fuel cells. *IEEE Trans. Energy Convers.* 179–190 (2008)
7. Iqbal, M.: Simulation of a small wind fuel cell hybrid energy system. *Renew. Energy*, 511–522 (2003)
8. Rakht Ala, S.M., Ghaderi, R., Ranjbar, A., Fadaeian, T., Nabavi, A.: Current stabilization in fuel cell/battery hybrid system using fuzzy-based controller. In: Presented at the IEEE Conference on Electrical Power & Energy, Canada (2009)
9. Na, W.K., Gou, B., Diong, B.: Nonlinear control of PEM fuel cells by exact linearization. *IEEE Trans. Ind. Appl.* 1426–1433 (2007)
10. Fardoun, A.A., Hejase, H.A., Al-Marzouqi, A.: Electric circuit modelling of fuel cell system including compressor effect and current ripples. *Int. J. Hydrogen Energy*, **42**(2), 1558–1566 (2017)
11. Rakhtala, S.M., Shafiee Roudbari, E.: Fuzzy PID control of a stand-alone system based on PEM fuel cell. *Electr. Power Energy Syst.* **78**, 576–590 (2016)
12. Utkin, V., Wenguang, Y., Longya, X.: Sliding mode pulse width modulation. In: American Control Conference, ACC'07, pp. 4530–4550 (2007)
13. Dave, M., Vyas, S.R.: Simulation and modelling of single phase dc-ac converter of solar inverter. *Int. Res. J. Eng. Technol. (IRJET)* **02**, 2225–2236 (2015)
14. Bimbhra, P.S.: *DC-DC Power Converters Power Electronics*. ISBN: 817409279X (Edition 2012)