Solid State Technology
Volume: 63 Issue: 4
Publication Year: 2020

Comparison of Controllers used in Fuel Cell for Power Conditioning

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Abstract— Fuel Cell (FC) is one of the most promising alternative sources of energy as it is pollution free and gives better power density than other renewable sources. As it does not depend on the weather conditions it is very useful source of energy. In this paper, performance of evaluation of different controllers used in mathematical expression and modelling of 500W BCS Stack is developed with some important characteristics. Power conditioning unit is connected to get useful voltage from FC. Power conditioning unit consists of Boost converter to raise the DC voltage of FC, and inverter is used to convert DC voltage into AC voltage. Two types of control schemes are employed to control the duty cycle of boost converter, which are PI controller and Fuzzy logic controller. Outputs of both controllers are comparatively investigated with important results.

Keywords: *PI controller; FLC; PEM Fuel Cell; SPWM, and LC filter*

I. INTRODUCTION

As the population of world is increasing and hence the requirement of energy is resulting in “energy crisis” [1]. To overcome this energy crisis, world is moving towards the renewable sources of energy like solar, wind, biomass, geothermal etc. Among all these, FC is a technology which gives promise to combustion free and clean source of energy. FC works on the principal of electrochemical conversion of energy. In FC chemical energy is converted into electrical energy by the reaction of fuels (hydrogen and oxygen) [2]. Among different types of FCs, proton exchange membrane fuel cell (PEMFC) is most popular type as it gives best output and can be used in stationary as well as transportable applications

A. Chemistry of A PEM Fuel Cell:

A PEM fuel cell shown in Fig. 1 consists of an anode, cathode, electrolyte membrane and catalyst [3]. Hydrogen is applied on the anode and oxygen is applied on cathode. While hydrogen is spitted into positive ions (proton) and negative ions (electron) due to catalyst, reaction takes place between positive ions of Hydrogen and Oxygen which produce water as byproduct while electron begin to flow in external circuit. Due to flow of electron, current begins to flows in the circuit connected to the anode and cathode.

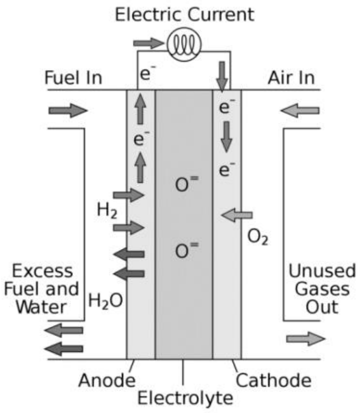


Fig. 1. Proton exchange membrane (PEM) Fuel Cell unit.

In Fig. 2 shows main components of fuel cell stacks are represented.

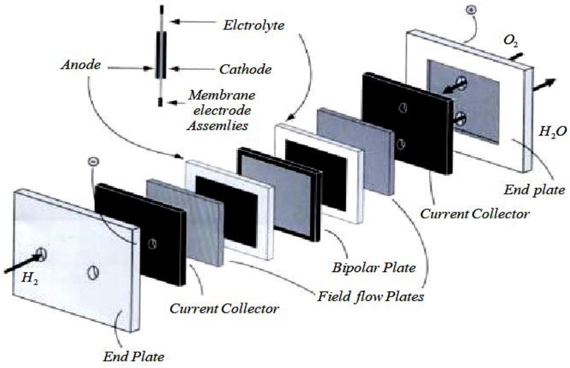


Fig. 2. Main components of Fuel Cell Stack.

Therefore, the reaction takes place is shown below [5].

At Anode

$$2H_2 = 4H^+ + 4e \qquad (1)$$

At Cathode

$$O_2 + 4H^+ + 4e^- = 2H_2O \qquad (2)$$

Net reaction

$$2H_2 + O_2 = 2H_2O + water + Heat \qquad (3)$$

B. Mathematical Modeling of A PEM Fuel Cell:

A fuel cell produces dc voltage which can be obtained from represented in following Equations (4), (5) and (6) represented by

$$V_{cell} = E_{nernst} - V_{act} - V_{con} - V_{ohmic} \qquad (4)$$

Here E_{nernst} is fuel cell voltage at no load or open circuit voltage of fuel cell. It is given as follows.

$$E_{nernst} = 1.229 - 0.85\times10^{-3}\left(T - 298.15\right) + 4.3085\times10^{-5}T\left[\log\left(PH_2\right) + 0.5\log\left(PO_2\right)\right] \qquad (5)$$

Where T is temperature, P_{H2} is Hydrogen pressure and P_{O2} is oxygen pressure. Ideally a fuel cell produces nearly 1.2 V at no load condition but due to various chemical and physical reasons some losses occurs in fuel cell, hence the net output voltage reduces to nearly 0.5 V to 0.6 V. These losses can be described as follows [3-5, 6].

- Activation loss
- Concentration loss
- Ohmic loss

Activation Loss

This loss occurs due to slowness of the reactions. Some of the voltage is lost to drive the reaction which transfers the electron from electrodes as Equation (6).

$$V_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 T \ln\left(CO_2\right) + \xi_4 T \ln\left(I_{fc}\right)\right] \qquad (6)$$

Where ξ_1, ξ_2, ξ_3 and ξ_4 are constants, I_{fc} is Fuel Cell current and C_{O2} is concentration of oxygen given by

$$CO_2 = \frac{PO_2}{5.08 \times 106 \times e^{-498/T}}$$

Concentration Loss

This type of loss occurs due to change of concentration of fuel as they are taking part in the reaction as given Equation (7).

$$V_{con} = -B \ln\left(1 - \frac{j}{j_{\max}}\right) \qquad (7)$$

Where B is constant, J is current density and J_{max} is maximum current density.

Ohmic loss

This type of loss occurs due the material used for electrodes, electrolyte and various connections of the Fuel Cell stack. These all create resistance to the flow of ions; this loss is linear in nature represented by Eqs. (8).

$$V_{ohm} = I_{fc}\left(R_m - R_c\right) \qquad (8)$$

Where R_c is membrane resistance

$$R_m = \rho_m \times 1 / A$$

Where ρ_m is specific resistivity, l is thickness of membrane and A cell active area.

$$R_m = \frac{181.6\left[1 + 0.03\left(I_{fc}/A\right) + 0.062\left(T/303\right)^2\left(I_{fc}/A\right)^{2.5}\right]}{\left[\varphi - 0.634 - 3\left(I_{fc}/A\right)\right]\exp\left[4.18\left(\left(T-303\right)/T\right)\right]}$$

Where φ is parametric coefficient.

If total numbers of fuel cell in a stack are n then total fuel cell output is given Equ. (9), we get.

$$V_{FC} = n.V_{cell} \qquad (9)$$

On the basis of above equations, a fuel cell modeled in MATLAB/Simulink R2015a, is designed as shown in Fig. 3.

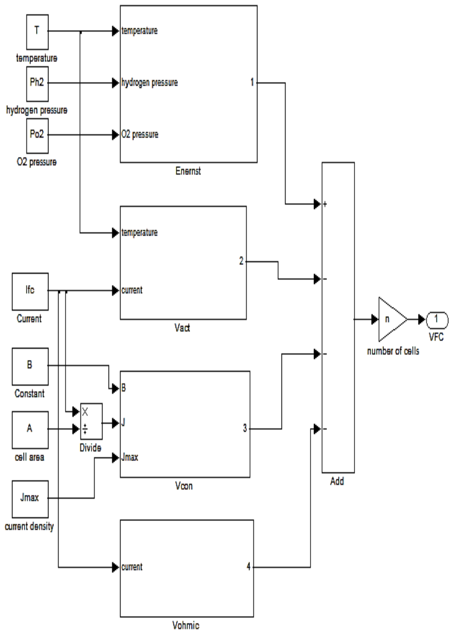


Fig. 3. Fuel cell Simulink model.

A characteristic curve between fuel cell current and voltage is shown in Fig. 4, initial drop of voltage shows the activation loss, medium drop shows the ohmic loss and last drop of voltage shows the concentration loss as associated with fuel cell [6].

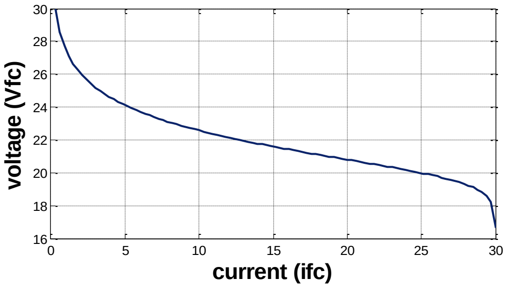


Fig. 4. Characteristic of 500W BCS Fuel Cell stack.

From Table 2. fuel cell parameters of 500 watts BCS stack.

Table 1: Fuel Cell parameters of 500W BCS Stack

Parameter	**Value**	**Parameter**	**Value**
n	32	ξ_1	-0.948
A	64 cm^2	ξ_2	0.00286+0.0002ln(A)+0.000043ln(C_{H2})
l	178 µm	ξ_3	7.6×10^{-5}
T	333 K	ξ_4	-1.93×10^{-4}
P_{o2}	0.2095 atm	φ	23
P_{H2}	1 atm	J_{max}	469/cm^2
R_c	3×10^{-4} Ω	C	3F
B	0.016 V		

C. Power Conditioner for Fuel Cell:

A Fuel Cell produces very low DC voltage. To take fuel cell in use, power conditioning devices are used. Boost converter is used to raise the DC voltage output of fuel cell (FC) and an inverter is used to convert DC voltage into AC voltage. A block diagram of typical fuel cell system is shown in Fig. 5.

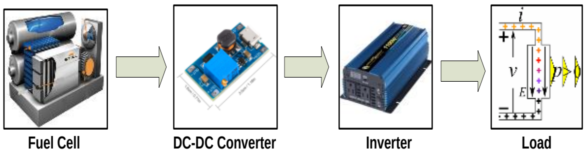


Fig. 5. Block diagram of a typical fuel cell system.

II. BOOST CONVERTER

DC voltage produced from fuel cell is very low. To increase this voltage boost converter is used. Boost converter raise the input voltage using the switching device (MOSFET) as shown in Fig. 6. On the basis of switching frequency applied to MOSFET, output voltage is obtained. This switching frequency is achieved by the comparison between actual output voltage and desired output voltage [7-8].

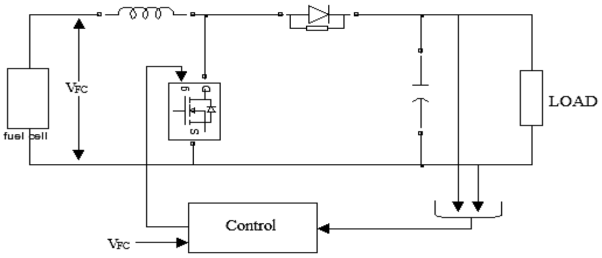


Fig. 6. DC-DC boost Converter.

Error signal generated from comparisons controlled by the controller as shown in Fig. 7. Output of this controller generates the switching pulse of the MOSFET of Boost converter.

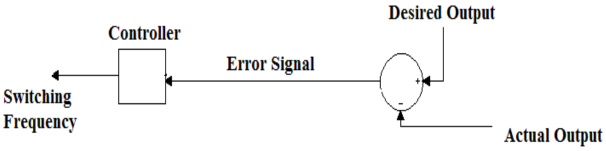


Fig. 7. Closed loop system of boost converter.

Two controllers namely PI controller and fuzzy logic controller are used for the purpose and results are compared [9], [10].

A. PI Controller

From Fig. 8 illustrated as PI controller is one of the most common types of controller used for the control purpose. It needs mathematical modeling of the system to compute the values of parameters k_p and k_i. k_p is the parameter to adjust the value of proportional controller and ki to control value of integral controller [11], [12], [13].

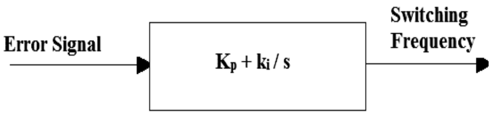


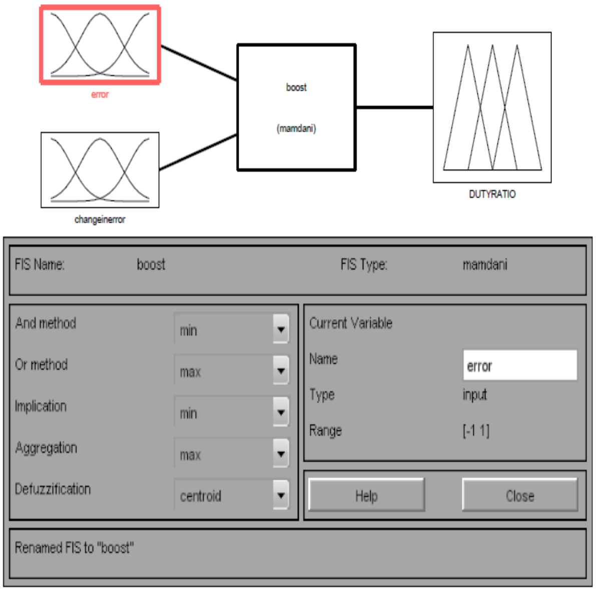
Fig. 8. Design of PI controller.

B. *Fuzzy Logic Controller:*

Rules for fuzzy logic control are derived from the practical knowledge of behavior of the system [14]. It does not need mathematical calculation hence it is very easy to construct. To implement the fuzzy based rule, error and change in error are taken as FIS variables as shown in Fig. 9 [15], [16]. Value of error and change in error are taken as following Equation (10) and (11).

$$e(n) = V_{out}(desired) - V_{out}(actual) \qquad (10)$$

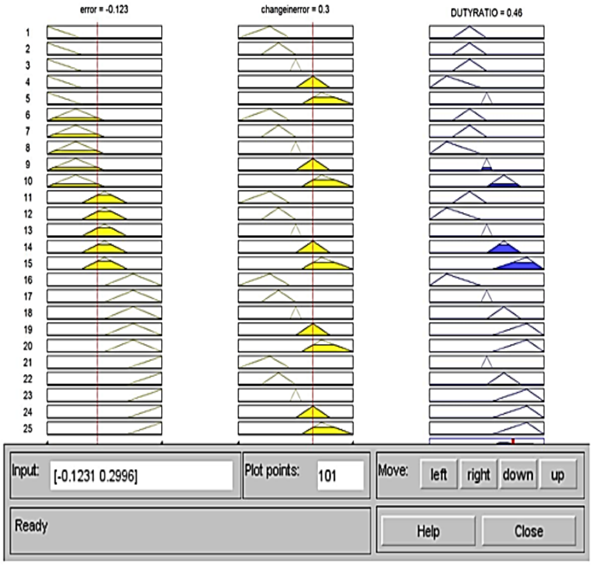
$$C_e(n) = e(n) - e(n-1) \qquad (11)$$



FIS Name: boost
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: error
Type: input
Range: [-1 1]
Renamed FIS to "boost"

Fig. 9. FIS variables for boost converter.

Rules of FLC are shown in Fig. 10.



Input: [-0.1231 0.2996]

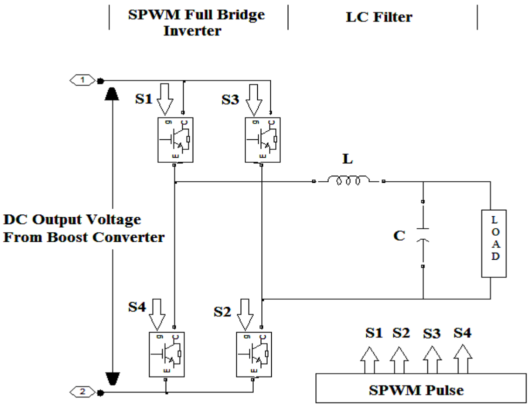
Plot points: 101

Ready

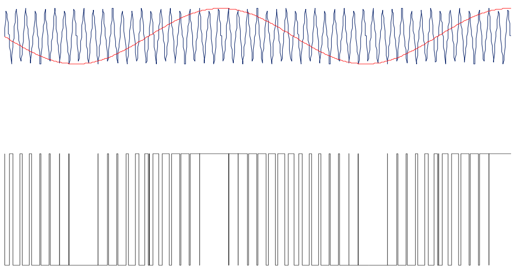
Fig.10. Rule Viewer of FLC

C. *SPWM Full Bridge Inverter:*

Output of boost converter is fed to the single phase SPWM inverter as shown in Fig. 11a-11b. Inverter converts the DC power to AC power for using AC power applications. Four IGBT are used as switching elements in this inverter. Sine wave of low frequency is compared with the triangular wave of high frequency to produce gate triggering signal to the IGBTs of inverter [16].



(a)



(b)

Fig. 11 (a) Circuit diagram of SPWM full bridge Inverter and **(b).** SPWM waveform.

D. *LC filter:*

An LC filter is used at the output terminals of inverter. The value of inductor and capacitor in LC filter are adjusted to get the closest sine wave output. This LC filter is shown in Fig. 11 (b) connected after inverter [9], [12].

III. Results and Discussions

Results of Boost Converter with PI controller and Fuzzy Controller are shown in Fig. 12 and Fig. 13. Results are compared in Table 2.

Table 2. Comparison of Boost Controller output

	PI Controller	**Fuzzy Controller**
Peak Overshoot	47.7194 V	No Oscillations
Settling Time	14.2ms	2.55ms

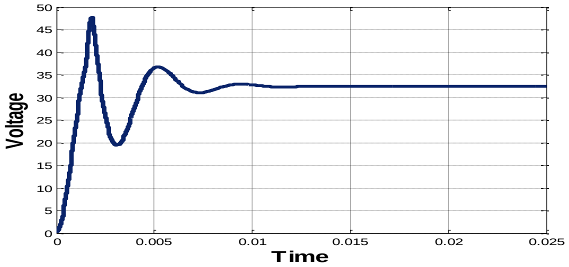


Fig. 12. Output of Boost Converter (PI Controller)

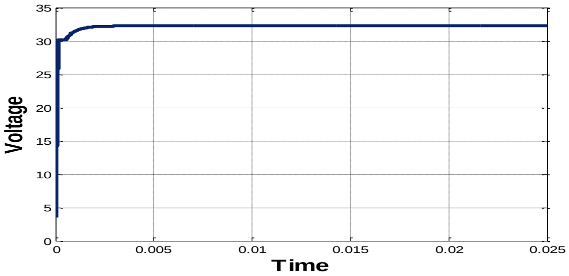


Fig. 13. Output of Boost Converter (Fuzzy Controller).

Results of Inverter with PI Controller and Fuzzy Controller are shown in Fig. 14 -15.

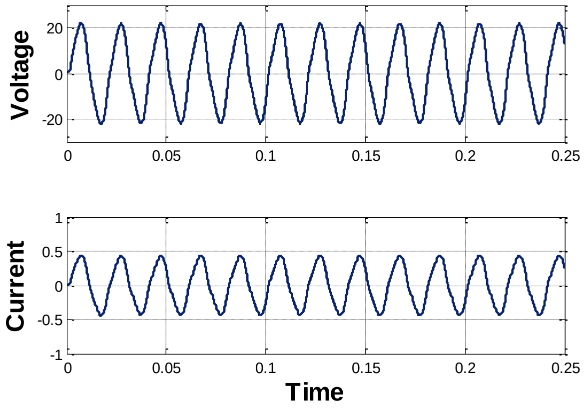


Fig. 14. Output of Inverter (PI Controller).

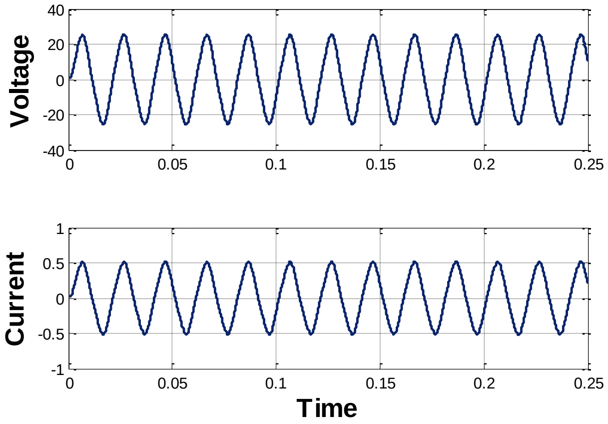


Fig. 15. Output of Inverter (Fuzzy Controller)

FFT analysis is done in the see Fig. 16 and 17 respectively.

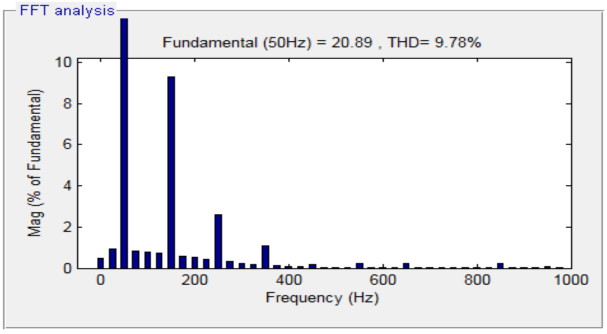


Fig. 16. FFT Analysis of output voltage at 1 KHz carrier frequency for 2 cycles (PI Controller)

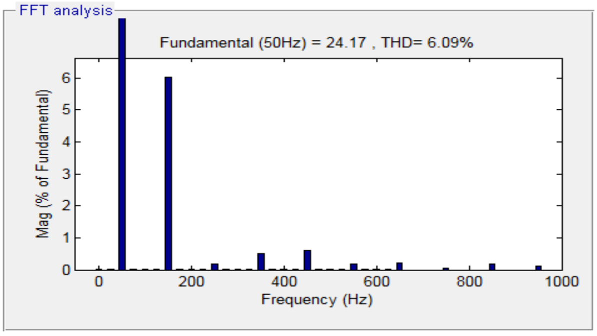


Fig. 17. FFT Analysis of output voltage at 1 KHz carrier frequency for 2 cycles (Fuzzy Controller)

Results of inverter are compared in Table 3.

Table 3. Comparison of THD both controller PI and FLC

	PI controller	**Fuzzy Controller**
THD	9.78	6.09

IV. CONCLUSION

In this paper the mathematical expression and modelling of 500 W BCS PEM Fuel Cell stack is developed and output of Fuel Cell is fed to the power conditioning unit to get required output for use in different application. Two types of controller's PI Controller and Fuzzy controller are used to control the output. With reference to Table 2 it is seen that settling time of PI controller is 14.2 ms while of Fuzzy controller is 2.55 ms and from Table 3, THD of Inverter output from PI controller is 9.78 % and from Fuzzy controller is 6.09 %. So, it can be said that Fuzzy controller is better than conventional PI controller.

V. ACKNOWLEDGMENT

This work was financially supported by World Bank Technical Education Quality Improvement Program (TEQIP)-III Project of Rajkiya Engineering College, Ambedkar Nagar (U. P.)-224122.

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