Fuzzy logic control of fuel cell based power source for aerospace applications

JENICA ILEANA CORCAU
Department of Electrical, Energetic and Aerospace Engineering
University of Craiova, Faculty of Electrical Engineering
Blv. Decebal, nr. 107, Craiova, Dolj, ROMANIA
LIVIU DINCA
Department of Electrical, Energetic and Aerospace Engineering
University of Craiova, Faculty of Electrical Engineering
Decebal Blv., nr. 107, Craiova, Dolj, ROMANIA
TEODOR LUCIAN GRIGORIE
Department of Electrical, Energetic and Aerospace Engineering
University of Craiova, Faculty of Electrical Engineering
Blv. Decebal, nr. 107, Craiova, Dolj, ROMANIA
ALEXANDRU TUDOSIE
Department of Electrical, Energetic and Aerospace Engineering
University of Craiova, Faculty of Electrical Engineering
Blv. Decebal, nr. 107, Craiova, Dolj, ROMANIA

Abstract: - The paper presents the modelling, control and numerical simulation of a power source based fuel cell-PEM. The power source includes a fuel cell stack model, reformer model and dc to dc boost converter model. A fuzzy logic controller (FLC) is used to control the flow rate methane in the reformer. The membership functions for inputs and output are Gaussian type, the max-min inference method is used for fuzzification, while the centroid method is used for deffuzification. Simulation results obtained using Matlab/Simulink, SimPower Systems, Fuzzy Logic Toolbox are presented to verify the effectiveness of the proposed control algorithm.

Key-Words: - Dc to dc boost converter, PEM fuel cell, Fuzzy Logic Control, Matlab/Simulink-SimPower Toolbox

1 Introduction

Intensive researches in the fuel cells field have been developed since 1960, and are still in developing at this time, both globally and nationally. Their space level uses were extended to extremely varied terrestrial applications – the power supply of residential or industrial areas, road vehicles – cars, buses, airport utility vehicles, then it moved their uses even on UAV aircrafts boards, as well as on transport aircrafts, replacing auxiliary power sources – APU [1]-[5].

The interfacing between the fuel cells and the bus, as well as the bus voltage adjustment, is made via the dc to dc converters. They have developed immensely and they continue to develop along with the power electronic devices. The constructive versions are extremely various, depending on the applicability domain: industrial, domestic, on space vehicles board, vessels and aerospace systems.

2 Fuel cell model

Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into electrical energy.

The model of fuel cell used in this study is based on the dynamic Proton Exchange Membrane Fuel cell (PEMFC) development in references [6], [7]. This model is based on simulating the relationship between output voltage and partial pressure of hydrogen, oxygen and water. The relationships between the molar flow of hydrogen through the
valve and its partial pressure inside the channel can be expressed \[6\], \[7\]

\[
\frac{q_{H_2}}{p_{H_2}} = K_{H_2}
\]

(1)

In this case for hydrogen molar flow, there are three significant factors: hydrogen input flow, hydrogen output flow and hydrogen flow during the reaction. The relationship between these factors can be expressed as \[6\]

\[
\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} (q_{in}^{H_2} - q_{out}^{H_2} - q_{an}^{H_2})
\]

(2)

where \(V_{an}\) is volume of the anode channel.

According to the basic electrochemical relationship between the hydrogen flow and FC system current, the flow rate of reactant hydrogen is given in \[7\]

\[
q_{in}^{H_2} = \frac{N_0 I_{FC}}{2F} = 2K_r I_{FC}
\]

(3)

Where \(N_0\) is number of cells in the stack series; \(F\) is Faraday’s constant; \(I_{FC}\) is stack current; \(K_r\) modeling constant.

Similarly, the water partial pressure and oxygen partial pressure can be obtained. The polarization curve for the PEMFC is obtained from the sum of Nernst’s voltage \((E)\), the activation over voltage \((\eta_{act})\) and the ohmic over voltage \((\eta_{ohmic})\) \[6\], \[7\]

\[
V_{cell} = E + \eta_{act} + \eta_{ohmic}
\]

(4)

\[
E = N_0 \left[ E_0 + \frac{RT}{2F} \log \frac{P_{H_2}}{P_{H_2,0}} \right]
\]

(5)

\[
\eta_{act} = -B \ln (C \cdot I_{FC})
\]

(6)

\[
\eta_{ohmic} = -R_{out} \cdot I_{FC}
\]

(7)

The model Matlab/Simulink for this PEMFC is realized using the equations above. The parameters are given in \[6\].

3 Dc to dc boost converter model

To connect a fuel cell to an external power system it is necessary to boost the fuel cell voltage or to increase the number of cells. The role of the dc to dc boost converter is to increase the fuel cell voltage, to control the fuel cell power, and to regulate the voltage. In figure 1 shows the dc to dc converter model \[8\]-\[11\].

![Fig.1 The dc to dc boost converter](image)

In figure 1 the switch is typically MOSFET, IGBT or BJT. It is a class of switching-mode power supply containing at least two semiconductor switches (a diode and transistor) and at least one energy storage element. Filters made of capacitors are normally added to the output of the converter to reduce output voltage ripple.

This circuit consists of two distinct states: 1) in the on-state, the switch S is closed, resulting in an increase in the inductor current; 2) in the off-state, the switch S is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R.

The output voltage of a dc boost converter, during continuous conduction mode is \[9\]

\[
V_{out} = \frac{V_{in}}{1 - d},
\]

(8)

where \(d\) is duty cycle. It represents the fraction of the commutation \(T\) during which the switch S is on. The ranges \(d\) is between 0 (S is never on) and 1 (S is always on).

This boost converter is described by the following non-linear state space averaged equations \[9\]

\[
\frac{dI_L}{dt} = -\frac{R_L}{L} \left( 1 - d \right) V_C + \frac{1}{L} V_{in}
\]

(9)

\[
\frac{dV_C}{dt} = \frac{1 - d}{C} I_L - \frac{I_0}{C}
\]

The peak-to-peak ripple current for a boost converter is \[9\]

\[
\Delta I = \frac{V_{in} \cdot d}{f \cdot L},
\]

(10)

The peak-to-peak ripple voltage across the capacitor for a boost converter, functions of average load current \(I_0\), switching frequency \(f\) and capacitance \(C\) is \[9\]

\[
\Delta V_{out} = \Delta V_C = \frac{I_0}{f \cdot C}.
\]

(11)

From equations (10) and (11), the value for inductor \(L\) and capacitance \(C\) are found \[9\]

\[
L = \frac{V_{in} \cdot d}{f \cdot \Delta I},
\]

(12)
4 Reformer model

In [12] the author introduced a simple model of a reformer that generates hydrogen through reforming methane. The model is second-order transfer function. The mathematical form of the model can be written as follows [12]

\[
\frac{q_{H_2}}{q_{\text{methane}}} = \frac{CV}{\tau_1 \cdot \tau_2 s^2 + (\tau_1 + \tau_2) s + 1},
\]

where \( CV = 2 \) is conversion factor [kmol of hydrogen per kmol methane]; \( \tau_1 = \tau_2 = 2 \) are reformer time constants. Considering the fuel cell as a source, the converter boost dc to dc and load connection is shown in figure 2.

![Fig. 2 Fuel cell dc to dc converter system connection](image)

To design control strategy for FC power plant, two parameters should be considered and regulated. These parameters are hydrogen flow according to output power and FC current. Using equations (2) and (3) to control hydrogen flow from the FC, a feedback from the stack current is considered.

A PD (proportional-derivative) fuzzy controller is used to control the flow rate methane in the reformer. Oxygen flow is determined using the hydrogen-oxygen flow ratio \( r_{H_2-O} \). The control strategy for reformer is illustrated in figure 3.

![Fig. 3 The control strategy for reformer](image)

5 PD Fuzzy Logic Controller

Fuzzy logic controller does not need an accurate mathematical plant model. Furthermore, a fuzzy logic based controller is designed, because the cost of the controller design and implementation is relatively low and it has a high performance/cost ratio. Fuzzy set theory uses fuzzy inferencing to reason about linguistic variables, i.e. variables described by fuzzy sets. A number of different inference systems have been developed [14]-[18].

In fuzzy control it is, however, two inference systems that dominate: Mamdani fuzzy systems, also known as linguistic fuzzy systems and Takagi-Sugeno fuzzy systems.

Fuzzy control is also nonlinear and adaptive in nature and offers robust performance under parameter variations and load disturbances.

In this case the controller is Proportional derivative (PD) conventional fuzzy controller having inputs the error \( e(k) \) and change of error \( ce(k) \). The output of the controller is the duty ratio of the hydrogen flow \( u_{H_2}(k) \).

The error, change of error and output of the controller are given [12]

\[
e(k) = q_{H_2} + q_{\text{meth.ref}} - q_{H_2},
\]

\[
ce(k) = e(k) - e(k - 1),
\]

\[
u_{H_2}(k) = u_{H_2}(k - 1) + \rho \Delta u_{H_2}(k),
\]

Where \( q_{H_2} \) is the flow hydrogen from the current feedback signal were is proportional to the load, \( q_{\text{meth.ref}} \) is the methane reference signal, \( q_{H_2} \) is the hydrogen flow feedback signal, \( \Delta u_{H_2}(k) \) is the inferred change of duty ratio by fuzzy controller and \( \rho \) is the gain factor of the controller.

The linguistic term for error, change of error and output are: NB (Negative Big), NM (Negative Medium), ZO (Zero), PM (Positive Medium) and PB (Positive Big).

Fuzzy rules are: If \( e(k) \) is NB and \( ce(k) \) is NB then \( \Delta u_{H_2}(k) \) is NB; If \( e(k) \) is NB and \( ce(k) \) is NM then \( \Delta u_{H_2}(k) \) is NB; If \( e(k) \) is NB and \( ce(k) \) is ZO then \( \Delta u_{H_2}(k) \) is NM; If \( e(k) \) is NB and \( ce(k) \) is PM then \( \Delta u_{H_2}(k) \) is NM; If \( e(k) \) is NB and \( ce(k) \) is PB then \( \Delta u_{H_2}(k) \) is ZO; If \( e(k) \) is NM and \( ce(k) \) is NB then \( \Delta u_{H_2}(k) \) is NB; If \( e(k) \) is NM and \( ce(k) \) is ZO then \( \Delta u_{H_2}(k) \) is ZO; If \( e(k) \) is NM and \( ce(k) \) is ZO then \( \Delta u_{H_2}(k) \) is ZO; If \( e(k) \) is NM and \( ce(k) \) is PM then \( \Delta u_{H_2}(k) \) is ZO; If \( e(k) \) is
The centroid defuzzification method determines the output value from center of gravity of the output membership function and is given by the expression [11], [12]

\[
\Delta u_H^2 = \frac{\sum_{i=0}^{n} \mu_e(u_H^2) \cdot u_H^2}{\sum_{i=0}^{n} \mu_e(u_H^2)}.
\]

The inference method used in basic and simple; it is developed from the minimum operation function rule as a fuzzy implementing function. It utilized Min-Max method and in figure 7 is presented the control surface.

6 Simulations results

In order to show the effectiveness of proposed control strategy, simulation model of fuel cell dc to dc converter system has been built in Matlab/Simulink software. This model is presented in figure 8 and in figure 9 is presented the model of dc to dc boost converter realized in SimPowerSystems using the mathematical and electrical models of the system described earlier.
The PEMFC model has been built using the relationship between output voltage and partial pressure of hydrogen, oxygen and water. The PEMFC presents a model of a 6 kW, 45V, proton exchange membrane PEM feeding an average value 100 Vdc dc to dc boost converter. The simulations produce the followings results. In figure 10 is presented the stack dc voltage (fuel cell) under a step current (0 to 134A). The power converter is controlled with a PI controller to regulate the voltage bus at 100 V by adjusting the duty cycle. Thus, dc output load voltage is kept at 100 V. Figures 10 to 13 show the simulation results for dc to dc converter, i.e. output voltage of the dc to dc converter, output current of the dc to dc converter and the variation of duty cycles for dc to dc converter corresponding to load demand.

7 Conclusion
Modelling, control and simulation study of a fuel cell based power source is presented. The power source includes a dynamic fuel cell model, reformer model, dc to dc converter model and fuzzy logic controller model. Then the developed model is tested using step change in the load current.
demands. The model Matlab/Simulink has a modular structure that can be implemented, simulated and analyzed with different parameters of any desired PEMFC system. Also a PD (proportional-derivative) fuzzy controller is used to control the flow rate methane in the reformer.

References: