

## **Fuzzy-PID controller for PEM Fuel cell in Automobile Application**

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**ABSTRACT:** A fuel cell (FC) is an electro-chemical device that converts chemical energy to electrical energy by combining a gaseous fuel and oxidizer. New advances in membrane material, reduced usage of noble metal catalysts, and efficient power electronics have put the fuel cell system under the spotlight as a direct generator for electricity. Of all the varieties of fuel cells, the Proton Exchange Membrane (PEM) fuel cell has shown the effectiveness for automotive applications because of their lower operating temperature(50-100<sup>0</sup>C)s and fast start-up times. They can reach efficiencies of above 60% at normal operating conditions. A typical PEM-FC provides up to 0.6 W/cm<sup>2</sup> depending on the catalyst loading, the membrane and electrode material, and the reactant (oxygen O<sub>2</sub> & hydrogen H<sub>2</sub>) concentration in the anode and cathode. To satisfy different power requirements, many FCs are connected electrically in series to form a FC stack (FCS). Maintaining a fuel cell system in correct operating conditions requires good controller. Based on the mathematical model of proton exchange membrane fuel cell, a fuzzy logic controller in the feed forward path and a PID controller in the feedback path was designed for the PEM FC to make it possible to output constant voltage .

**Keywords** - breathing control, **fuel** cell stack, fuzzy controller, oxygen starvation, PEM FC, PID

### **I. INTRODUCTION**

The world is facing an energy crisis as well as significant environmental problems. It is well known that fossil fuels such as petroleum, natural gas and coal are the main resources for generating electricity and at the same time major contributors to environmental problems. Renewable energy is viewed as one of the ways to alleviate the current global warming crisis. Major efforts are devoted towards developing alternative electricity production methods [1, 2]. Fuel cells are promising energy sources that produce electrical currents with almost null pollutant emissions. Fuel cell technology plays an important role in the development of alternative energy. In the recent years there was an increasing interest in fuel cell technology. Fuel cells can operate continuously as long as the necessary fuel flows are maintained. Fuel cells differ from batteries in that they do not need recharging, they operate quietly and efficiently, and when hydrogen is used as fuel they generate only electric power and drinking water. So, they are called zero emission engines. One of the most interesting fuel cells types is the proton exchange membrane fuel cell (PEMFC) due to its high efficiency [3], and it is one of the promising technologies for power generation in future [4]. The PEM-FC takes its name from the special plastic membrane used as the electrolyte. This membrane electrode assembly (MEA), not thicker than a few hundred microns, is the heart of a PEM-FC and, when supplied with fuel and air, generates electric power at cell voltages around 0.7 V and power densities of up to about 1 W/cm electrode area. The ionomeric membrane has exclusive proton permeability and it is thus used to strip electrons from hydrogen atoms on the anode side. The protons flow through the membrane and react with oxygen to generate water on the cathode side, producing a voltage between the electrodes. When the gases are pressurized, the fuel cell efficiency is increased, and favorable conditions result for smooth flow. Pressurized operation also allows for better power density, a key metric for automotive applications. Furthermore, the membrane must be humidified to operate properly, and this is generally achieved through humidification of supplied air flow [5].

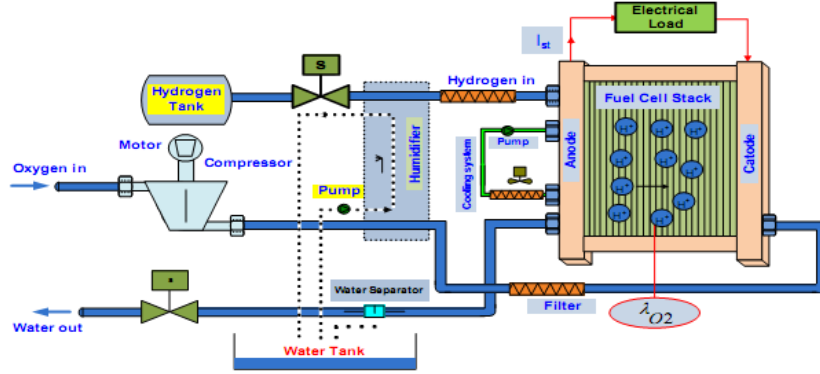


Fig 1 PEM-FC

## II. FUEL CELL POWER GENERATION

Typically, the FC characteristics are given in the form of a polarization curve, which is the plot of FC voltage versus current density. The current density,  $i$ , is defined as current per active area,  $i = I_{st}/A_{fc}$ . Since fuel cells are connected in series to form the stack, the total stack voltage is  $V_{st} = n \cdot V_{cell}$  and the stack power is  $P_{st} = V_{st} \cdot I_{st}$ . Part of the stack power is used to drive the compressor motor. Therefore, the net power,  $P_{net} = P_{st} - P_{cm}$ . The FC polarization curve is a function of cathode pressure, reactant partial pressures, FC temperature and membrane humidity. The activation overvoltage,  $V_{act}$ , ohmic overvoltage,  $V_{ohm}$  and concentration overvoltage,  $V_{conc}$ , each affects a different region in the polarization curve.

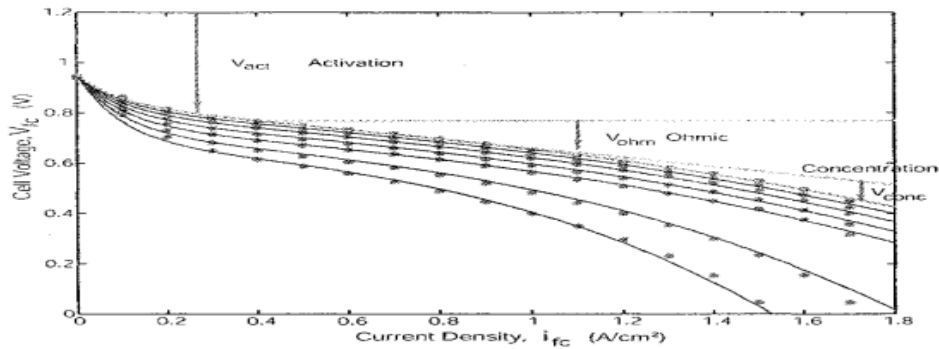


Fig 2 Polarization Curve

The output voltage of a single cell can be defined by the following expression [6].

$$V_{fc} = E_{ernst} - V_{act} - V_{ohm} - V_{conc} \quad (1)$$

The FC voltage is calculated by subtracting the fuel cell losses or over voltages from the fuel cell open circuit voltage,  $E_{ernst}$ .  $E_{ernst}$  is the thermodynamic potential of the cell representing its reversible voltage.

$$E_{ernst} = 1.229 - 0.85 \cdot 10^{-3} (T_{fc} - 298.15) + 4.31 \cdot 10^{-5} T_{fc} [\ln(P_{H_2}) + \frac{1}{2} \ln(P_{O_2})] \quad (2)$$

From equation (2) it is inferred that the cell voltage can be varied by changing either of operating pressure, partial pressure of the reactants, operating temperature and membrane hydration. In practice the operating pressure (usually atmospheric pressure) and temperature are bounded to be fixed where the performance of the cell is optimal. The variations in the stack temperature are insignificant when the temperature is controlled. Therefore the effect of stack temperature on voltage can be neglected under transient conditions. On the other hand, the dynamics on anode side reactant supply are negligible due to the fact that the  $H_2$  is supplied from a high pressure cylinder. Therefore the stack voltage depends mainly on the partial pressure of oxygen (supplied in the form of air) and conductivity of protons which depends on the hydration of the membrane. Finally, the cell voltage can be controlled by manipulating the oxygen concentration provided the

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membrane water content remains same during load changes . Oxygen is supplied in the form of air using an air compressor. Therefore any variations in stack voltage at a given current are attributed by compressor motor voltage. In connection with the control problem, the PEM fuel cell system results in two inputs (compressor motor voltage, stack current) and two outputs (stack voltage, net power).

2.1. FUEL CELL STACK SYSTEM

The fuel cell model documented in [9] will be applied to the feed-back (FB) and feed-forward (FF) controllers . The fuel cell stack (FCS) model simulated consists of four interacting sub-models which are the stack voltage, the anode flow, the cathode flow, and the membrane hydration models. The voltage model contains an equation to calculate stack voltage that based on fuel cell temperature, pressure, reactant gas partial pressures and membrane humidity.

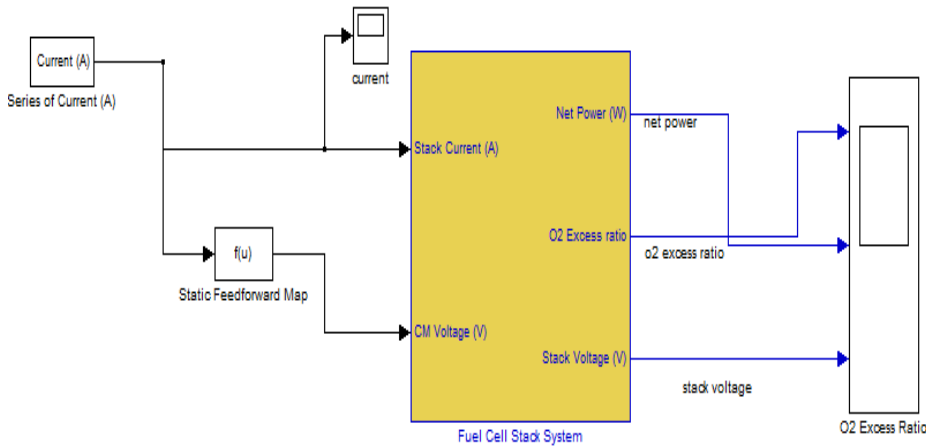


Fig 3 Fuel Cell Stack Model

**III. FUEL CELL CONTROL TECHNIQUES**

The FC air flow needs to be controlled rapidly and capably to avoid oxygen starvation and extend the life of the FC stack [7]. Oxygen starvation is a complicated phenomenon that occurs when the partial pressure of oxygen falls below a critical level at any location within the meander of the air stream in the cathode [8]. This phenomenon entails a rapid decrease in cell voltage, which in severe cases can cause a hot spot, or even burn-through on the surface of a membrane. Although the oxygen starvation is spatially varying, this phenomenon can be avoided by regulating the cathode excess oxygen ratio  $\lambda_{O_2}$  . We thus regulate air ratio in the FCS cathode by controlling compressor motor voltage  $V_{cm}$  during step changes in current drawn  $I_{st}$  from the FCS.

Feed-forward (FF) controller is used to generate directly an input voltage of the compressor according to the current demand. The fuzzy logic controller is used as the FF controller to control of the fuel cell, since the fuzzy logic is relatively simple and is based on definitions of formal facts and the relationships among them. Then, a PID controller is used in the feedback to adjust the difference between the requested and the actual oxygen ratio by compensating the feed-forward controller output. The performance variables are excess oxygen ratio  $y=\lambda_{O_2}$  in the fuel cell cathode.

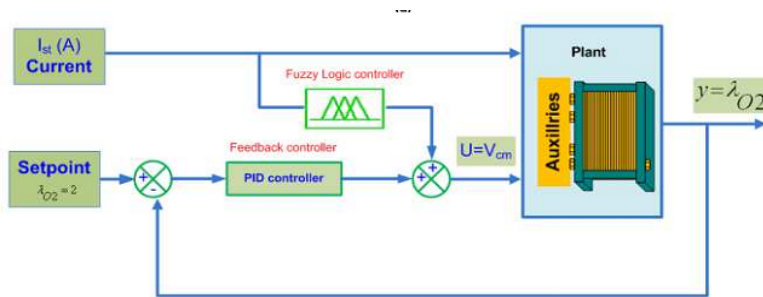


Fig 4 PEM-FC with Fuzzy PID Controller

Fuzzy controller is designed , where the inputs of fuzzy controller is the fuel cell stack current "100~ 300A" (the current demand), and its output  $\Delta$ output (the change of compressor voltage

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100~235 V). The membership function for the input and output fuzzy logic controller is divided to low, med low, normal, med high, high. The steady state value between the control input,  $V_{cm}$ , & the disturbance,  $I_{st}$ , could be used in the feed forward path. For specific ambient conditions (pressure, temperature & humidity), the required air flow can be calculated analytically from the stack current based on electrochemical & thermodynamic principles.

The fuzzy logic controller was executed by setting the membership functions for inputs and outputs which are stack current and voltage respectively. The input and output are related by rules that were formulated on the needs.

R1	If current is low	then $\Delta$ voltage is low	Else
R2	If current is med low	then $\Delta$ voltage is med low	Else
R3	If current is normal	then $\Delta$ voltage is normal	Else
R4	If current is med high	then $\Delta$ voltage is med high	Else
R5	If current is high	then $\Delta$ voltage is high	Else

Table 2. Fuzzy logic controller rules

A defuzzification strategy aims to produce a non-fuzzy control action that best represents the possibility distribution of the inferred fuzzy control actions. In real-time implementation of fuzzy logic control, the commonly used defuzzification strategies are the mean of maximum (MOM), the centre of Maximum (COM), the centre of area (COA) and the center of Gravity (COG). The centre of area (COA) is selected for the defuzzification process in this paper.

The PID controller is used as the Feed-Back (FB) controller which is the most widely used controller. Over 85% of all dynamic controllers are of the PID variety. The acronym PID stands for Proportio-Integro-Differential control. Each of these, the P, the I and the D are terms in a control algorithm, and each has a special purpose. Sometimes certain of the terms are left out because they are not needed in the control design. This is possible to have a PI, PD or just a P control. It is very rare to have a ID control

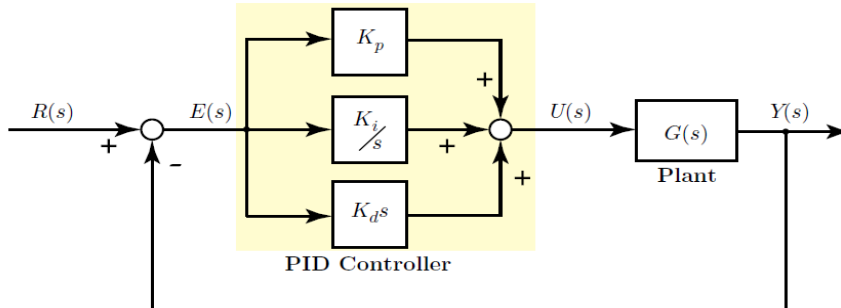


Fig 5 PID Controller

Ziegler-Nichols tuning rule is used to determine the value of  $K_i$ ,  $K_p$  and  $K_d$  which is based on the transient step response of a plant. It can be applied to plants with neither integrators nor dominant complex-conjugate poles, whose unit-step response resemble an S-shaped curve with no overshoot. This S-shaped curve is called the reaction curve.

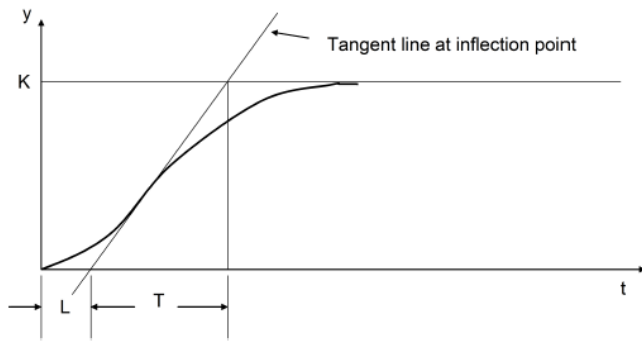


Fig 6 S-curve

The S-shaped reaction curve can be characterized by two constants, delay time  $L$  and time constant  $T$ , which are determined by drawing a tangent line at the inflection point of the curve and finding the intersections of the tangent line with the time axis and the steady-state level line. Using the parameters  $L$  and  $T$ , we can set the values of  $K_p$ ,  $K_i$  and  $K_d$  according to the formula shown in the table below.

Controller	$K_p$	$K_i$	$K_d$
P	$T/L$	0	0
PI	$.9T/L$	$.27T/L^2$	0
PID	$1.2T/L$	$.6T/L^2$	$.6T$

Table 1: PID parameters affecting system dynamics

These parameters will typically give a response with an overshoot about 25% and good settling time. We may then start fine-tuning the controller using the basic rules that relate each parameter to the response characteristics. The controller is used in a closed-loop unity feedback system. The variable  $e$  denotes the tracking error, which is sent to the PID controller. The control signal  $u$  from the controller to the plant is equal to the proportional gain ( $K_p$ ) times the magnitude of the error plus the integral gain ( $K_i$ ) times the integral of the error plus the derivative gain ( $K_d$ ) times the derivative of the error.

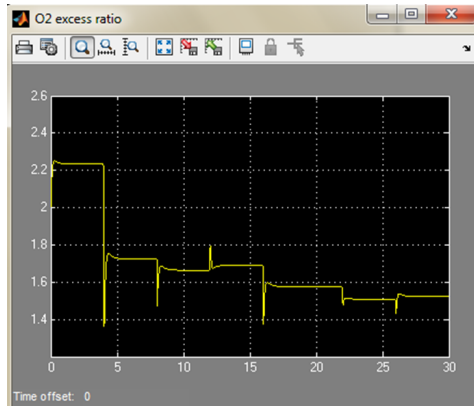


Fig 7:Oxygen excess ratio without controller

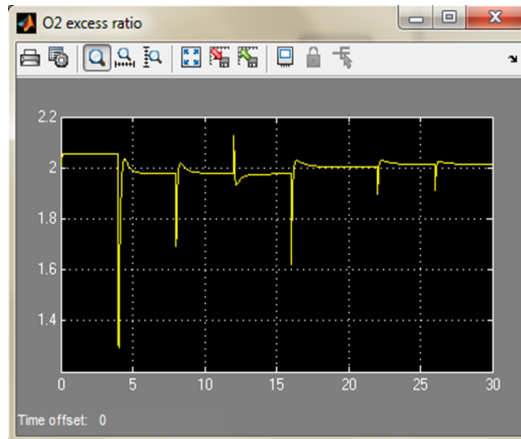


Fig 8: Oxygen excess ratio with controller

#### IV. CONCLUSION

Polymer electrolyte membrane (PEM) fuel cells has emerged as one of the most clean and promising alternatives to reduce fossil fuel dependency, but they have some shortcoming also, the Fuel Cell air flow needs to be controlled rapidly and capably, In order to avoid oxygen starvation during step changes of current demand and extend the life of the FC stack. Oxygen starvation entails a rapid decrease in cell voltage, this phenomenon can be avoided by regulating the cathode excess oxygen ratio  $\lambda_{O_2}$ . For this purpose a PID controller is used in the feedback FB to adjust the difference between the requested and the actual oxygen ratio by compensating the feed-forward controller output. After observing the stack voltage and net power and by comparing with fuel cell without feedback, it was noted that the PID controller along with the FLC performs well in regulating the oxygen ratio in the presence of changing demand of the load current. Simulation results show that the proposed controllers can give good control effects. Here we can see that the sudden increase and decrease in stack voltage (i.e. overshoot and undershoot respectively) is reduced to a considerable level.

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