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Fractional order PID control of air feed system in a proton exchange membrane fuel cell

Arun Kumar Pinagapani[a,*], S. Iniya[b]

[a] I & CE Department, PSG College of Technology, Coimbatore, Tamil Nadu, Inida
[b] Validation Team, Caterpillar India Engineering Solutions Private Limited, Chennai, Tamil Nadu, India

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Abstract

Proton Exchange Membrane Fuel Cell (PEMFC) converts chemical energy liberated during the electrochemical reaction of hydrogen and oxygen to electrical energy and has huge potential in transport, stationary and portable applications. It is an open loop stable system but it does not settle in the given set point. Hence controllers are required to make the system to settle at the set point and also to prevent the PEMFC from oxygen starvation. A simulative approach of controlling PEMFC with Proportional Integral Derivative (PID) controller and Fractional order PID (FOPID) controller is investigated in this paper. FOPID controller is tuned using two approaches namely KC auto tuning and Oustaloup approximation. The performances of the two FOPID controllers are compared with PID controller. The use of FOPID controller results in better closed loop time domain characteristics than PID controller and is shown with simulations in MATLAB.

Keywords: PEMFC, FOPID, PID, Controller, Fractional order.

1. Introduction

Fuel Cell (FC), for a decade has been an alternative source for the green energy for a wide range of applications. The distinguishing property of PEMFC from the other fuel cell is that it can operate at lower temperature ranges ($50°C$ to $100°C$). PEMFC technology has replaced the aging alkaline technology which are mainly used in the space shuttles. Since the PEMFC is a possible source of portable power sources and other industrial applications in future, maintaining the air feed system is critical, so that the fuel cell is prevented from oxygen starvation and flooding. Excessive flow of

*Corresponding author
Email addresses: arunkumarakshai@gmail.com (Arun Kumar Pinagapani), siva.iniya97@gmail.com (S. Iniya)

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oxygen may lead to flooding and insufficient flow may lead to starvation. PEM fuel cell contains compressor, a pressurized hydrogen tank, control valve for hydrogen supply and a cooling fan. Power output from PEMFC depends on the inflow of hydrogen and oxygen. Control valves regulate the pressure ratio difference between cathode and anode. When the supply of air to fuel doesn't meet the requirement, fuel cell leads to starvation which causes degradation. Hence, the oxygen excess ratio in the cathode side should be controlled for better operation of the fuel cell and the need for a controller is imminent.

In [3] the concept of fractional calculus and a brief tutorial on fractional calculus in controls is presented. They have introduced fractional order PID controllers and it led to the use of FOPID in industry. Future research efforts in fractional order control are also remarked in this paper. The authors [7] illustrated the fractional order PI/PD and PID controllers which enhances the robustness of the closed system under study. They have utilized KC auto tune method for tuning the fractional order controllers. The key advantage of auto tuning method is that it eliminates the complex procedure with nonlinear equations as in traditional fractional order controller design.

The authors [16] presented the concept of fractional order PID controllers and also the minimal optimization methods. They have also compared fractional calculus and traditional integer order calculus based controllers. The comparison shows that fractional order calculus can be applied to a complex dynamic system which is more accurate than the integer order calculus.

An effective control strategy is implemented to avoid cell starvation. [8] presents the adaptive control based on model predictive Control. [13] presents the system modeling and the control of PEMFC.

In [15], four fractional-order controllers that are available in literature, namely, CRONE controller, TID controller, $PI^{\lambda}D^{\mu}$ controller and fractional lead-lag-compensator are compared. In [4] methods for avoiding the starvation of fuel and also thermal, water management and power control subsystems in a FC are reviewed critically. The authors [10] illustrated in the detail the information about the fractional order and controls in their book. In [2], fractional order fuzzy PID control of automotive PEMFC air feed system is dealt in detail. The authors [12] highlighted the advantages and problems in non-integer differentiation and its subsequent used in the real time operations. Also, they elaborated the concepts with real and complex orders to any frequency bandwidth. A new approximation method of the fractional-order Laplacian operator s^{α} is introduced along with its analytical proof and this approximation is based on a weighted sum of first-order filter sections [1]. In [5] comparison of four well-known methods for the rational approximation of fractional-order operator is done. In [11] a novel nonlinear disturbance observer based robust model-free adaptive interval type-2 fuzzy sliding mode control for a PEMFC system is proposed. The objective is to manipulate the oxygen ratio at the desired reference under varying load disturbances and uncertainties. By this way the oxygen starvation is eliminated and maximum net power is obtained.

2. PEMFC System And Model

PEM fuel cell has a pressurized tank, control valve for hydrogen supply, compressor and a cooling fan. The output power from a PEMFC depends on the flow rate of oxygen and hydrogen. Control valves are used to regulate the pressure ratio difference between anode and cathode. When the supply of air to fuel (ratio) does not meet the requirements, it may lead to starvation thus causing degradation of PEMFC. Hence, the oxygen excess ratio (OER) in the cathode side has to be controlled for efficient operation of PEMFC.

The model of PEMFC in [9] transfer function representation is

$$G(s) = 0.1268/(0.0141s + 1) \tag{2.1}$$

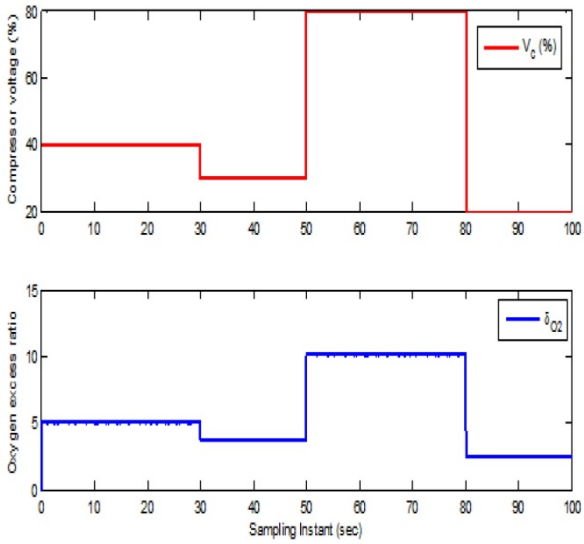

Figure 1: Open loop response of the model

and the discrete state space model of PEMFC is given by

$$x(k+1) = 0.00083157x(k) + 0.0141u(k) \tag{2.2}$$

$$y(k) = 8.9929x(k) \tag{2.3}$$

Equation (2.2) and (2.3) are obtained by converting the continuous time transfer function in equation (2.1) to discrete state space model with a sampling time of 0.1 second in MATLAB. It is a single state variable model with compressor voltage as input and oxygen excess ratio as output. The open loop response of PEMFC is shown in Fig 1.

3. Controller Design And Simulation

Two controllers namely PID and FOPID controllers are designed and simulated in this work. FOPID controller tuning parameters are obtained through KC auto tuning and Oustaloup approximation methods. The methodology of closed loop control strategy is shown in Fig 2. The compressor voltage (V_c) is the manipulated variable and the oxygen excess ratio (δ_{O2}) is the controlled variable. Oxygen from atmospheric air is given to the PEMFC via the compressor. Hydrogen tank supplies the required fuel for PEMFC to operate. The flow rate of hydrogen is kept constant and only the flow rate of air is manipulated to prevent oxygen starvation and flooding.

The generic form of a FOPID controller is the $PI^{\lambda}D^{\mu}$ and is shown in Fig 3 [6]. Both λ and μ can be any real numbers. It involves a differentiator of order μ and an integrator of order λ.

A. KC auto tuning
KC- Auto tuning method used for tuning FOPID is given in the below equations [14].

$$C_{PID} = K_P(1 + K_P s^{-\beta} + K_D s^{\beta}) \tag{3.1}$$

To find the value of β

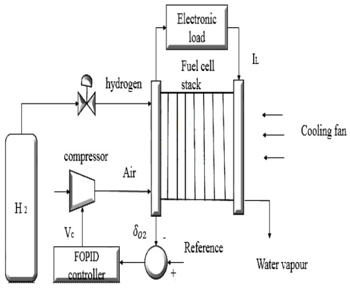

Figure 2: Block diagram of FOPID Controller Implementation

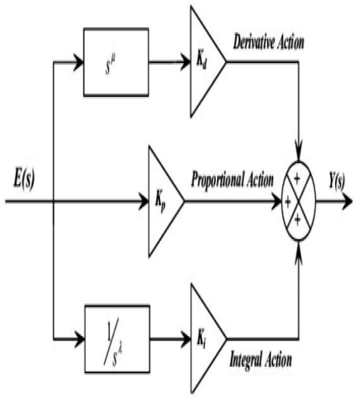

Figure 3: Generic FOPID controller

$$\beta = \left\| \frac{dIm}{dRe} - \frac{d\Im L}{d\Re l} \right\| \tag{3.2}$$

$$\frac{-Re(\alpha) + c}{Im(\alpha)} = \frac{dIm}{dRe} \tag{3.3}$$

Where $c = \frac{1}{\cos(PM)}; \alpha = 90^\circ - PM$

$$\frac{d\Im L}{d\Re l} = \frac{dL(j\omega)}{d\omega}; \omega = \omega_c \tag{3.4}$$

$$\frac{dL(j\omega)}{d\omega} = \frac{\cos\alpha}{\sin\alpha} + c \tag{3.5}$$

(PM – Phase Margin)

B. Oustaloup Approximation

Oustaloup approximation [12] is used for controlling the OER to prevent flooding and starvation. It involves recursive approximation and the two additional tuning parameters λ and μ gives two additional degree of freedom for a conventional PID controller.

$$D^v f(t) = \begin{cases} \frac{1}{\gamma(n-v)} \frac{d^n}{dt^n} \int_0^t (t-\tau)^{n-v-1} f(\tau) d\tau, & v > 0; \\ \frac{1}{\gamma(-v)} \int_0^t (t-\tau)^{-v-1} f(\tau) d\tau, & v < 0 \end{cases} \tag{3.6}$$

Where $n - 1 \leq v < n$; n is an integer $\gamma(x) = \int_0^{\propto} e^{-t} t^{x-1} dt$ is the gamma function

The Oustaloup approximation is given by To find the tuning parameter of β and μ

Table 1: PID Parameter Values

Parameter	K_P	K_I	K_D
values	1.3	4.991	0.2

Table 2: PID Parameter Values

Parameter	β	μ
KC Auto tune	1	0.7
Oustaloup Approximation	1.2	0.8

$$\beta = 1 + v\mu = 1 - v \tag{3.7}$$

To find the value of v

$$v = K_e \prod_{i=1}^{N} \frac{1 + \left[\frac{s}{\omega_{z,i}}\right]}{1 + \left[\frac{s}{\omega_{p,i}}\right]} \tag{3.8}$$

$$-1 \leq v < 1$$

$$K_e = \frac{(1 + 10^{-\delta})(1 + 10^{-\delta-2})}{(1 + 10^{\delta})(1 + 10^{\delta-2})}$$

$$\delta = \left[\frac{\omega_H}{\omega_L}\right]^N \tag{3.9}$$

$$\omega_{z,i} = \sqrt{\delta\omega_L} \quad \omega_{p,i} = k\omega_{z,i} \quad k = \left[\frac{\omega_H}{\omega_L}\right]^{\frac{1}{N}} \tag{3.10}$$

N is the order of the system
ω_H, ω_L are the cut off frequency

Tuning parameters of PID controller is obtained Z - N tuning method and is given in Table 1. FOPID controllers are designed using the equations (3.1), (3.2), (3.3), (3.4), (3.5) for KC auto tuning and equations (3.6) to (3.10) for Oustaloup approximation method. The resulting tuning values are tabulated in Table Controller parameters are calculated and shown in Table 2.

Fig. 4 shows the comparison of PID controller and KC auto tuned FOPID controller. Fig. 5 shows the comparison of PID and Oustaloup approximation based FOPID. The desired OER is set as 3 in both the cases.

Table 3 presents the detailed analysis of simulation results of PID and FOPID controller performance in closed loop. It is observed that the FOPID Oustaloup Approximation gives the better response in terms of rise time, settling time peak time and does not give any offset controller with two different tuning methods. It is seen that both PID and FOPID Oustaloup Approximation does not gives offset. FOPID KC Auto Tune also gives better time domain characteristics. Thus, the FOPID Oustaloup Approximation gives the better response in terms of rise time, settling time peak time and does not give any offset.

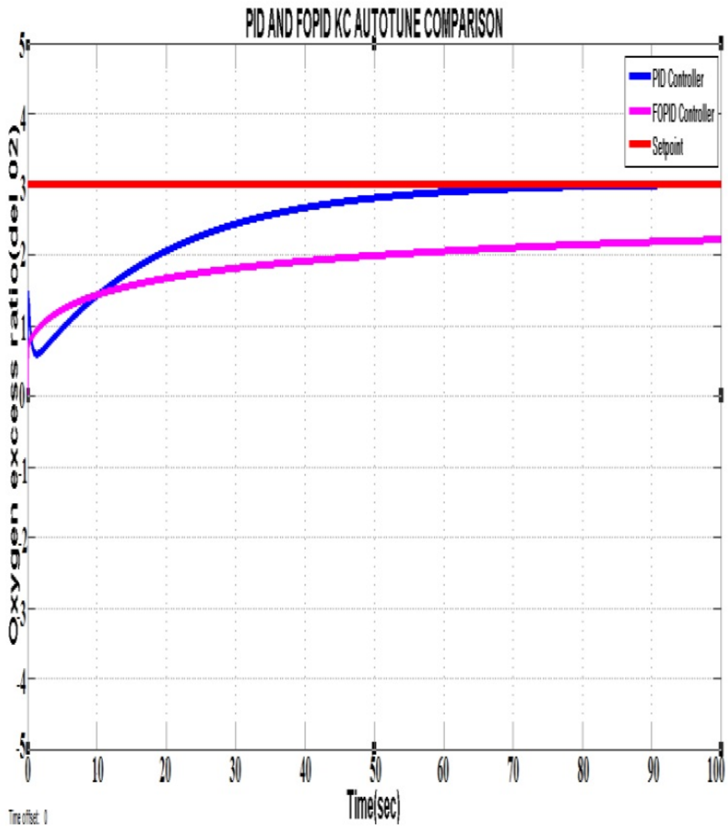

Figure 4: Comparison of PID and FOPID KC Auto tune of the system

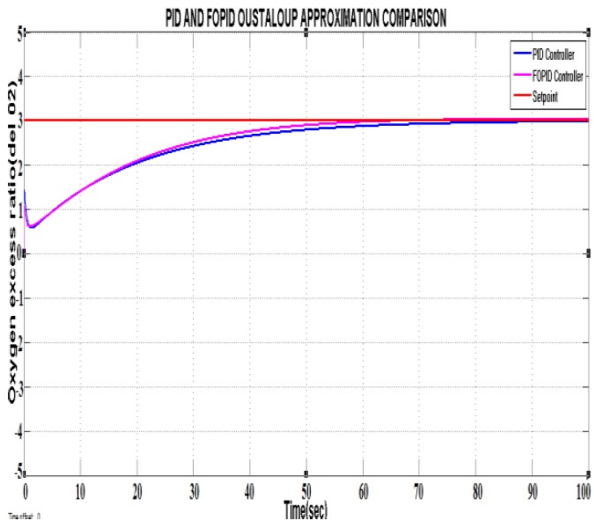

Figure 5: Comparison of PID and FOPID Oustaloup Approximation of the system

Table 3: Performance Measure

RESPONSE CHARACTERISTICS	**PID CONTROLLER**	**FOPID KC AUTO TUNE**	**FOPID OUSTALOUP APPROIMATION**
Settling time (seconds)	65	Does not settle	50
Rise time(seconds)	35	10	15
Peak time(seconds)	50	10	30
offset	0	2.5	0

4. Conclusion

The control of Oxygen Excess Ratio in a PEMFC is implemented using classical PID controller and FOPID controller. The PID controller is tuned using Z-N method. FOPID controller is tuned using KC Auto Tune and Oustaloup Approximation method. The controlled variable is OER. In order to prevent the cell from starvation, the compressor voltage is used as manipulated variable. From simulation results, it is inferred that both PID and FOPID controller gives satisfactory performances. FOPID controller tuned using Oustaloup Approximation is found to be better than KC Auto Tune method. PID controller and FOPID controller (Oustaloup Approximation) does not give offset. Rise time, peak time, settling time are found to be less in FOPID controller tuned using Oustaloup Approximation than conventional PID controller.

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