A NEW FUZZY ADAPTIVE PID CONTROLLER APPROACH DESIGN FOR SOLID OXYDE FUEL CELL POWER PLANT

Fayssal OUAGUENI [1, 2,*], Kada BOUREGUIG [3], Abdelghafour HERIZI [1, 2]
[1] Department of Electrical Engineering, Faculty of Technology, University of M'sila, Algeria
[2] Laboratory of Electrical Engineering (LGE), University of M'sila, Algeria
[3] Departement of Mechanical Engineering, Ibn Khaldoun University, Tiaret, Algeria
[*] Corresponding author, e-mail: fayssal.ouagueni@univ-msila.dz

Abstract

Solid Oxide Fuel Cells (SOFCs) are electrochemical devices operating at high temperatures, directly transforming chemical energy into electrical energy, offering significant potential as a clean and efficient power generation technology. The primary challenge concerning SOFCs is the intricacy of regulating the output voltage. This challenge is attributed to the strong nonlinearity, swift load variations, and restricted fuel flow. The primary objective of the SOFC system's control is to maintain a constant level of the output voltage respecting the safety intervals of the fuel utilization rate and the oxy/Hyd ratio. In this context, a new adaptive fuzzy PID controller (FPID) approach is proposed to control the output voltage of the SOFC nonlinear system, where two FPIDs controllers were used one for the hydrogen flow and the other for the oxygen flow. Simulation results are presented to demonstrate the effectiveness and accuracy of the proposed approach in front of other control strategists that use a constant ratio between the reactants.

Key words: Solid Oxide Fuel Cell (SOFC); nonlinear system; fuzzy controller; PID controller; fuzzy PID controller.

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I. INTRODUCTION

Fuel cells (FCs) are electrochemical converters that transform the chemical energy of a combustible gas or liquid into electrical energy. Hydrogen is the most widely used fuel in fuel cells. In certain fuel cells, methanol can also use as a direct fuel source. Among the new "clean" and "efficient" technologies used for the production of electricity, Due to their environmental benefits (minimal emission of harmful gases) and their high electrical and energy efficiency, fuel cells are considered highly promising [1,2].

Solid oxide fuel cells (SOFCs) are taking an important place within the large family of fuel cells. Because the possibility of operating with an internal reformer, the flexibility of fuel choice, and the high operating temperature (ranging from 973°K to 1273°K), the SOFC have been used in wide applications. The high temperature of SOFC can increase the yield of the fuel cell with cogeneration [3].

The main problem in the SOFC is the difficulties to control the output voltage due to slow dynamics, strong system non-linearity, rapid changes of the load, the limited fuel flow and tight constraints of the SOFC. Hence, when the load changes, the output voltage of SOFC cannot be kept constant and the fuel utilization rate may be out of the safety interval, this has a great impact on the lifetime of the SOFC. In this context, several intelligent control strategies have been proposed for the nonlinear SOFC system, like the conventional proportional-integral-derivative (PID) control [4-6], fuzzy control [7-9], fuzzy PID control (FPID) [10], neural network control [11, 12] and different methods of predictive control [13-18].

A FPID controller combines the PID control structure with fuzzy logic. Fuzzy logic allows for the handling of imprecise or uncertain information and is particularly useful when dealing with complex, nonlinear, or uncertain systems. FPID controllers adapt the gains (Kp, Ki, Kd) of a conventional PID controller using fuzzy rules that relate the error and its rate of change to the adjustments required in the control action. The fuzzy logic part introduces linguistic variables and membership functions to quantify terms like "low," "medium," and "high" for the error and its rate of change. These linguistic terms are then combined through fuzzy rules to determine how much to adjust each of the PID gains. The adjustment process is based on human-like reasoning and allows the controller to adapt to changing conditions and deal with nonlinearities more effectively.

In summary, while PID controllers provide a traditional approach to control systems, FPID controllers enhance this approach by incorporating fuzzy logic to handle uncertain and nonlinear situations more adeptly. The FPID approach aims to improve control performance by making real-time adjustments to the PID gains based on fuzzy rules and linguistic variables.

The FPID controller has been used to control the output voltage of the SOFC system in several works [10,19,20]. In these works the Hyd/Oxy ratio was fixed at an optimal value of 1.145. In this case, only one control variable is considered, namely hydrogen flow rate. However, not necessarily that Hyd/Oxy ratio exactly equals their optimal value. But it suffices that Hyd/Oxy ratio is in the vicinity of this value [13,16,17]. In this work, we will develop another approach of the FPID controller to control the SOFC's output voltage, where we will use two control variables i.e. two FPID controllers, one for the hydrogen flow and another for the oxygen flow. With the guarantee that the Hyd/Oxy ratio and the fuel utilization rate always remain within safe ranges. The simulation results will be discussed, interpreted and compared with the results of other works.

II. DESCRIPTION AND DYNAMICS ANALYSIS OF SOFC

II.1. Principle of operation

Like all types of fuel cells, SOFC transform the chemical energy of gaseous fuels (hydrogen, natural gas, methane, methanol, etc.) into electricity and heat by an electrochemical reaction. The operation principle of SOFC is illustrated in figure 1. The electrochemical reduction of oxygen (O_2) at the cathode leads to the formation of oxide ions (O^{2-}) which diffuse through the ion-conducting electrolyte to reach the anode material where occurs the electrochemical oxidation of the fuel (H_2) with simultaneous production of electricity, water and heat. The electrochemical reactions in SOFC are presented in the following manner:

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Anode reaction: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$

Cathode reaction: $1/2 O_2 + 2e^- \rightarrow O^{-2}$ (1)

Total reaction: $H_2 + 1/2 O_2 \rightarrow H_2O$

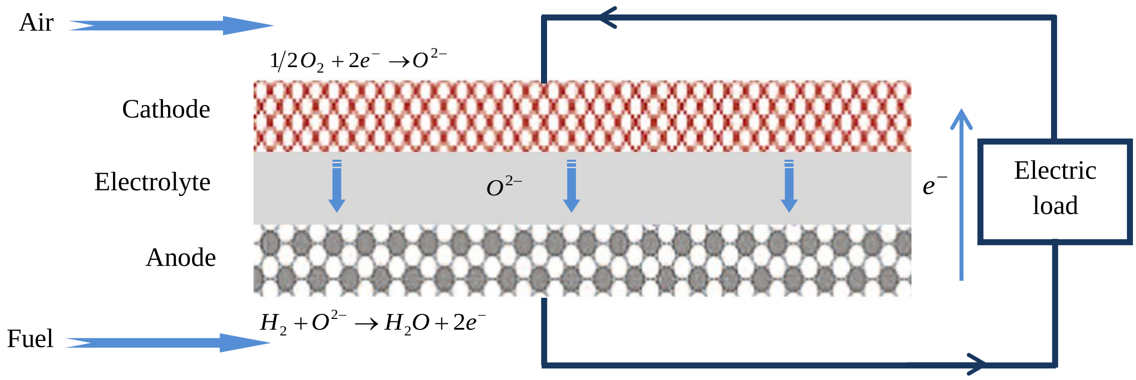

Figure 1. Schematic illustration of SOFC mechanism

II.2. SOFC system dynamic model

There are a large number of dynamic models to describe the chemical reaction present in a cell of SOFC. In this paper, we will take the dynamic model of SOFC developed in [21]. This model is widely used in several studies [9-11]. Its structure is illustrated in Figure 2, where V_s is output voltage of the stack (V), q_F is the fuel flow rate (mol/s), I_s is the external load current (A), q_H^{in} and q_O^{in} are the input molar flows of hydrogen and oxygen (mol/s), and P_{H_2}, P_{O_2}, P_{H_2O} are the partial pressures (Pa) of the hydrogen, oxygen, and steam, respectively. The remaining parameters of the model are illustrated in Table 1. The expressions for the partial pressures can be written as follows [22] :

$$P_{H_2} = \frac{1}{K_{H_2}(1+\tau_{H_2}s)}\left(\frac{1}{1+\tau_F s}q_F - 2K_r I_s\right) \quad (2)$$

$$P_{O_2} = \frac{1}{K_{O_2}(1+\tau_{O_2}s)}\left(\frac{1}{\tau_{H\_O}(1+\tau_F s)}q_F - K_r I_s\right) \quad (3)$$

$$P_{H_2O} = \frac{2}{K_{H_2O}(1+\tau_{H_2O}s)}K_r I_s \quad (4)$$

where $K_r = N_{cell}/4F$ is a reaction constant (mol/(s A)).

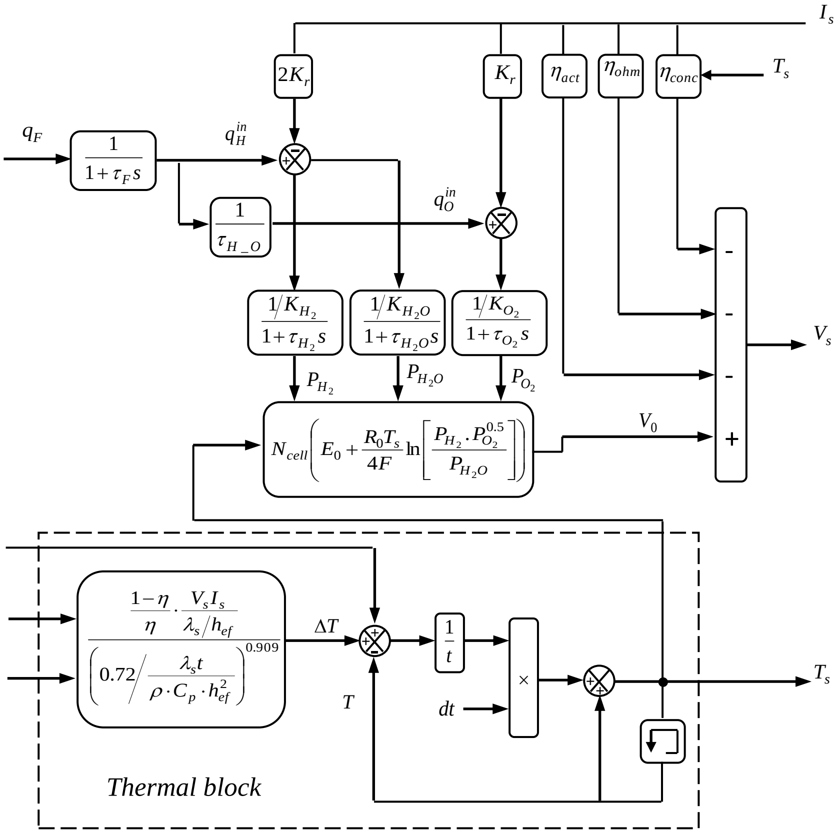

Figure 2. Block diagram of SOFC dynamic model

The application of Nernst's law on equations (1) gives the expression of the ideal stack voltage according to the operating conditions which is as follows:

$$V_0 = N_{cell}\left(E_0 + \frac{R_0 T_s}{4F}\ln\left[\frac{P_{H_2}.P_{O_2}^{0.5}}{P_{H_2O}}\right]\right) \qquad (5)$$

The different losses that appear at the SOFC stack during operation under load are:

Table 1 : Parameters in the SOFC system

Parameter	Value	Unit	Representation
R_0	8.314	J/(mol K)	Universal gas constant
T_0	973	K	Constant temperature
F	96.486	C/mol	Faraday's constant
E_0	1.18	V	Ideal standard potential
N_{cell}	384	-	Number of cells in the stack
K_r	0.993×10^{-3}	mol/(s A)	Reaction constant
K_{H_2}	8.32×10^{-6}	mol/(s Pa)	Valve molar constant for hydrogen
K_{O_2}	2.49×10^{-6}	mol/(s Pa)	Valve molar constant for oxygen
K_{H_2O}	2.77×10^{-6}	mol/(s Pa)	Valve molar constant for water
τ_{H_2}	26.1	s	Response time of hydrogen flow
τ_{O_2}	2.91	s	Response time of oxygen flow

τ_{H_2O}	78.3	s	Response time of water flow
τ_F	5	s	Time constant of fuel processor
r	0.126	Ω	Ohmic loss
∂	0.05	-	Tafel's constant
β	0.11	-	Tafel slope
I_l	800	A	Limiting current density

- ***The Ohmic loss*** is represented by the following expression:

$$\eta_{ohm} = rI_s \quad (6)$$

r is the total resistance of the cell, we can write it as :

$$r = r_0 \exp\left[\alpha\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right] \quad (7)$$

where α is a constant and r_0 is the cell's internal resistance at temperature T_0 .

- ***The activation loss*** is shown as follows:

$$\eta_{act} = \partial + \beta \log I_s \quad (8)$$

- ***The concentration loss***, this loss can be expressed by the following equation:

$$\eta_{conc} = \frac{R_0 T_0}{2F} \ln\left(1 - \frac{I_s}{I_l}\right) \quad (9)$$

After identifying the different losses, the expression of the output voltage of the stack is given as:

$$V_s = V_0 - \eta_{act} - \eta_{ohm} - \eta_{conc} \quad (10)$$

II.3. SOFC control

In this part, we will determine the reference values for the hydrogen and oxygen flow rates as well as the current flowing in the fuel cell. Several constraints must be applied between these three quantities in order to ensure correct operation in transients and optimal operation in steady state.

The optimal ratio between the inlet hydrogen flow and the inlet oxygen flow (reactants of fuel cell) is determined by the following expression:

$$r_{H\_O} = \frac{q_H^{in}}{q_O^{in}} \quad (11)$$

For SOFC system safety reasons, the ratio value is chosen so that the pressure difference between the pressures of hydrogen and oxygen ($\Delta P = P_{H_2} - P_{O_2}$) must not exceed 8 kPa in transient conditions and 4 kPa in normal conditions [23]. To maintain ΔP below 4 kPa under normal conditions, r_{H_O} must have a value of approximately 1.145 [24]. This value was determined after simulations carried out beforehand. 2053

Another important ratio to consider is the fuel utilization rate (U_f). This index serves as a performance metric for SOFCs, representing the proportion of consumed hydrogen flow (q_H^r) to the supplied hydrogen flow (q_H^{in}) within the fuel cell. Mathematically, it can be expressed as follows:

$$U_f = \frac{q_H^r}{q_H^{in}} = \frac{q_H^{in} - q_H^{out}}{q_H^{in}} = \frac{2K_r I_s}{q_H^{in}} \quad (12)$$

Usually, for high efficiency of SOFC, U_f is constrained between 70% and 90% with an optimal value at 80%.

II.4. Problem description and control objective

The objective of control design is to accurately maintain the output voltage at the rated level and minimize voltage fluctuations when there are changes in current loads. The following are the primary concerns in control design [10][11]:

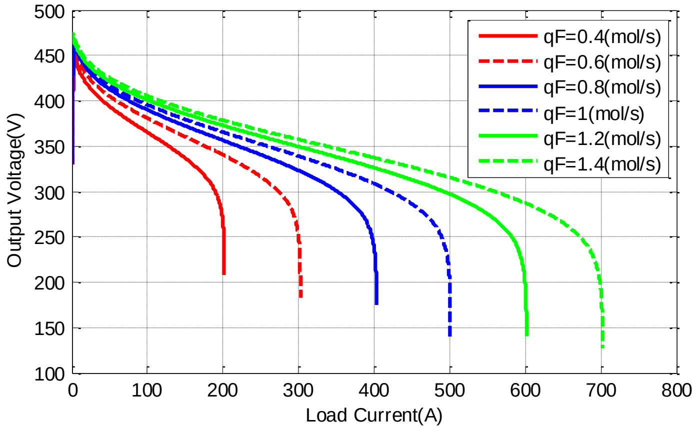

Figure 3. Voltage-current characteristics of the SOFC model in open-loop

- From the voltage-current characteristics of the SOFC model in open-loop illustrated in Fig. 3, it is evident that the SOFC demonstrates nonlinear behavior across a broad operating range. This nonlinearity is particularly prominent at low and high current loads, and when the current exceeds the maximum capacity, it results in a rapid decline in the stack's operating voltage. The stronger nonlinear characteristics of the SOFC system become more apparent under these conditions. Hence, a nonlinear SOFC controller is superior to a linear SOFC controller. The fuel flow must be limited within the range of 0 to 2 mol/s, which can lead to actuator saturation and potentially degrade the system's dynamic performance.
- The system exhibits hysteresis, where the rated voltage and load current load undergo rapid changes, while the impact of fuel flow on the output voltage occurs at a comparatively slower rate.

III. DESIGN OF FUZZY PID CONTROLLER FOR SOFC SYSTEM

A FPID controller is an industrial control system that combines the principles of PID control with fuzzy logic software. In automation, PID controllers are frequently utilized to manage valves and other process controls. These controllers operate by analyzing the cumulative error over time. However, a FPID controller distinguishes itself from a conventional PID controller by offering improved accuracy in nonlinear scenarios. Fuzzy systems rely on a programming logic that addresses the uncertainties and complexities of processes more effectively than traditional control methods.

Both FPID controllers and standard PID controllers rely on past data to compute future responses. The acronym PID itself represents this concept, where P represents current errors, I denotes past errors. and D signifies future error states. Fuzzy systems aim to map these errors in terms of their persistence and assign them to different membership sets corresponding to specific ranges of logical conditions. This enables a FPID controller to determine the rate of change required to bring the system back under control. This rate of change is determined based on inference rules, where accumulated data and error states indicate the most appropriate course of action.

In this paper, we propose a new fuzzy adaptive PID control structure of the SOFC system. The basic diagram's block of the system is depicted in figure 4, where two fuzzy controllers were used one for the oxygen flow and the other for the hydrogen flow. The inputs of the fuzzy adaptive PID controller are the error $e(k)$ and the change error $ce(k)$, they are given as:

$$e(k) = V_{s_{ref}}(k) - V_s(k) \quad (13)$$

$$ce(k) = e(k) - e(k-1) \quad (14)$$

where $V_{s_{ref}}(k)$ denotes the voltage reference, and $V_s(k)$ denotes the output voltage.

The control equation of the fuzzy adaptive PID is given as follows [10] :

$$u(t) = k_p e(t) + k_i \int [e(t) + Ku_2(t)] + K_d \frac{dV_s(t)}{dt} \quad (15)$$

$$u_2(t) = u_1(t) - u_0(t) \quad (16)$$

where $u(t)$ denotes the control action, k_p, k_i and k_d are respectively the proportional gain, integral gain and derivative gain.

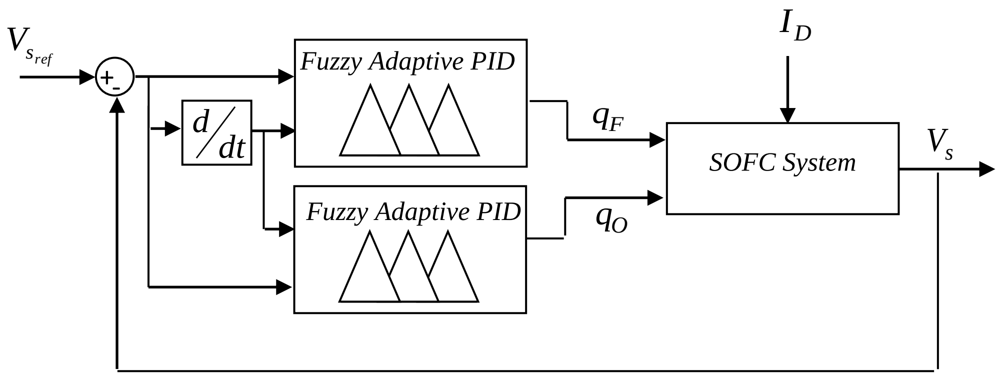

Figure 4: The block diagram illustrating the proposed fuzzy adaptive PID controller.

In order to formulate the fuzzy logic rule, a set of seven fuzzy items are defined : NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The fuzzy rules used to determine the values of the gains k_p and k_i are listed in table 2 and 3 respectively.

Table 2: Fuzzy rules of the k_p gain

k_p		$ce(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PM	PS	ZO	NS	NS
	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	ZO	NM	NM	NM	NB	NB

Table 3: Fuzzy rules of the k_i gain

k_i		$ce(k)$						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
$e(k)$	**NB**	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	PM	PB	PB

As shown in Fig. 5 [10], the membership functions of NM, NS, ZO, PS and PM are triangular type, while the type of the membership functions of NB and PB is Pi. The universe of discourse of k_p, k_i, $e(k)$ and $ce(k)$ are all [-3, 3], and with different gains between inputs and outputs and also between the two fuzzy controllers.

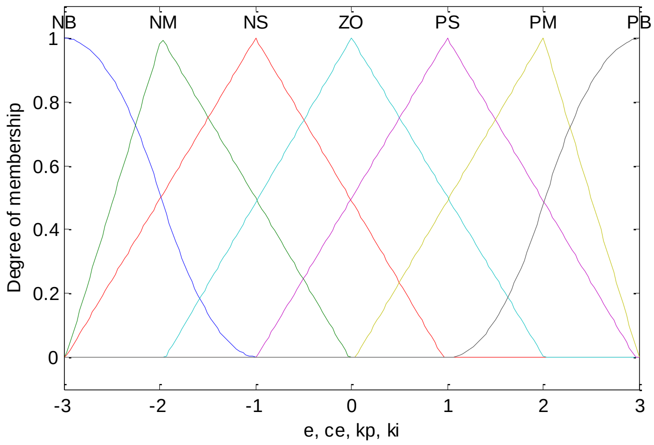

Figure 5: Membership functions of inputs and outputs

IV. SIMULATION RESULTS

In this section, a comparison is presented to demonstrate the robustness of the proposed controller developed in Section III (fuzzy adaptive PID control with two fuzzy controllers; FPID2) for the SOFC system, versus three other control methods; the conventional PID controller (with two PID controllers; PID2) and the two control methods with one controller developed in [10] namely; the conventional PID controller (PID1) and fuzzy adaptive PID control (FPID1). The comparison involves simulating the disturbance response. The simulation results are subsequently presented for analysis.

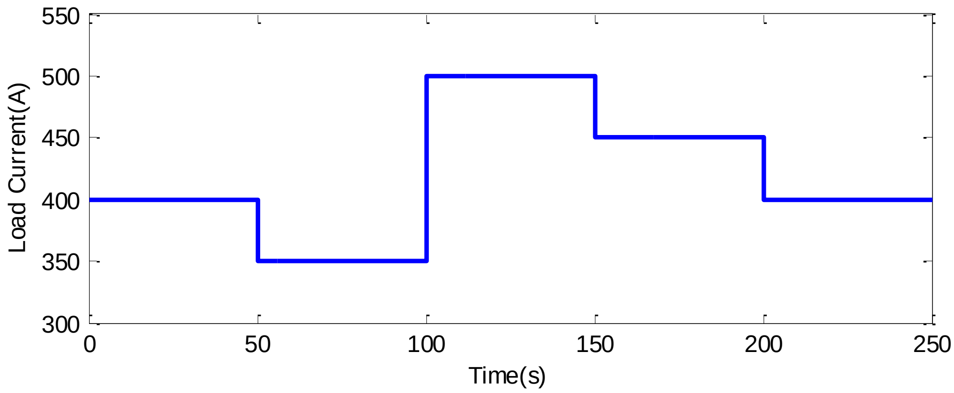

Fig. 6. Load current variation

Throughout the disturbance response process, the output voltage reference is considered constant, set at 305 V. In order to evaluate the performance of the SOFC system, we introduce a step change in the load current after every 50s, as follows; the load current starts with 400 A, then decreases by 50 A at 50 s, then increase from 350A to 500A at 100 s, and then it is set to decrease by 50 A at 150 s and 200 s (see Fig.6). The proposed FPID2 is considered here.

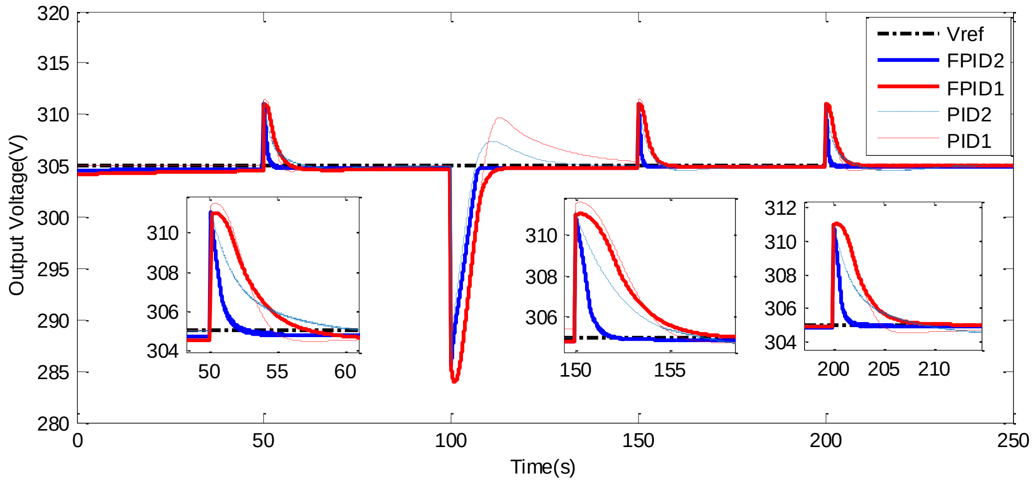

Fig. 7. Trajectories of SOFC voltage

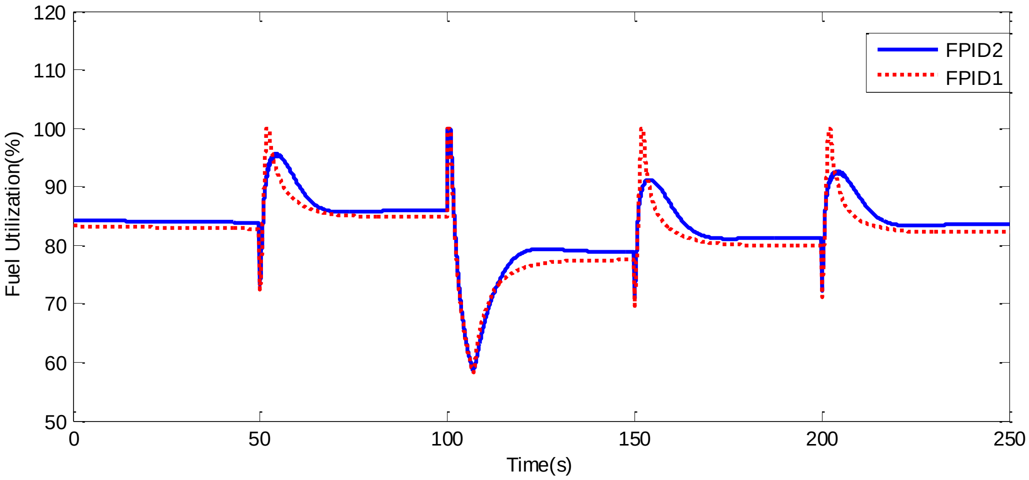

Fig. 8. Fuel utilization rate

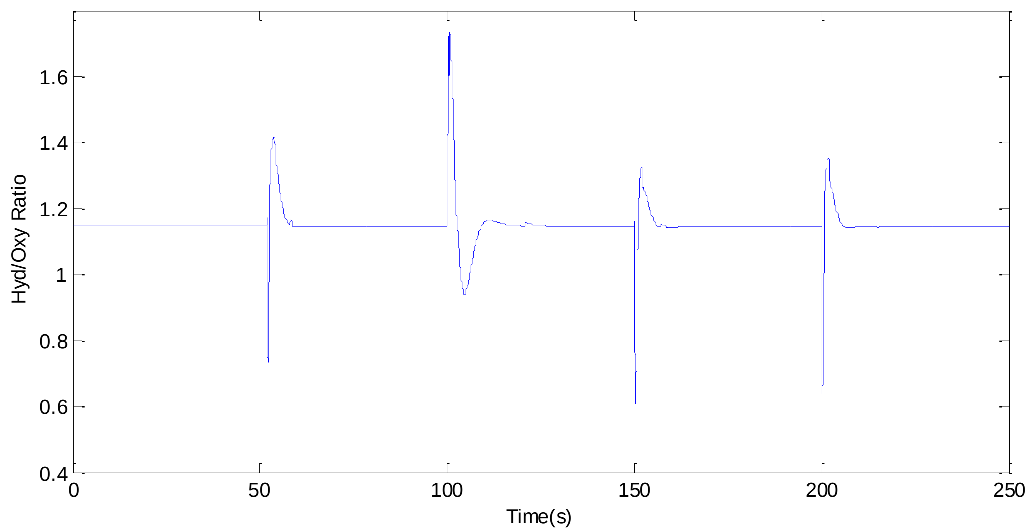

Fig. 9. Hyd/Oxy ratio

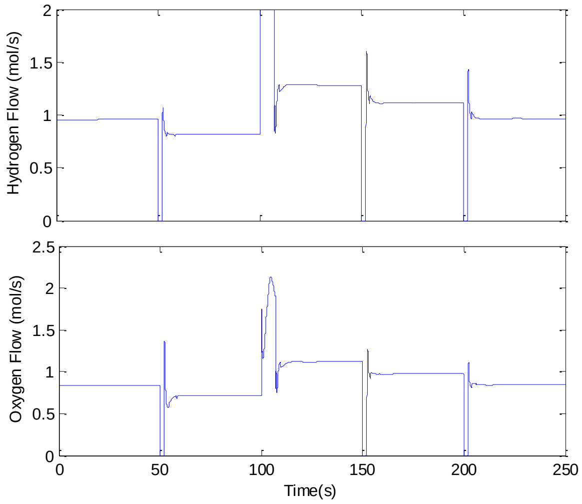

Fig. 10. Curves of inputs variables

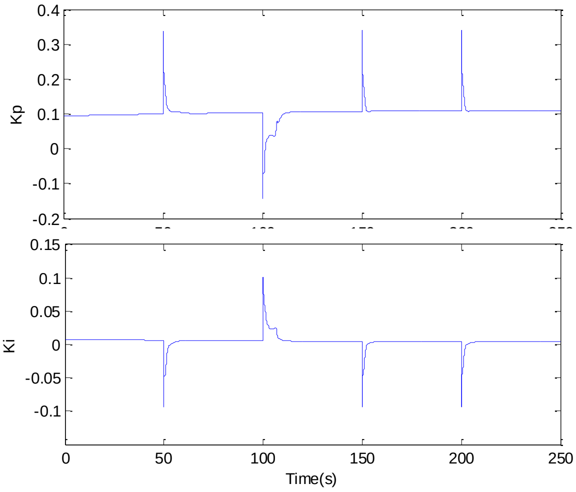

Fig. 11. Gains curves of FPID2 controller

As illustrated in figures 7-9, as the load current changes, the output voltage undergoes rapid changes before returning to its reference value, the fuel utilization rate stays within the required range and the Hyd/Oxy ratio is kept in the safety range, therefore, the proposed FPID2 can be applied to maintain the output voltage in its reference value and guaranteed all the SOFC's performances considered before. The curves of inputs variables of SOFC and the gains curves of the proposed controller are presented in figures 10 and 11, respectively.

Table 4. Performance Comparison

Controller	Index \ Number	1	2	3	4
FPID2	Overshoot (%)	0	0	0	0
	Settling Time (s)	3.84	7.13	2.25	3.11
FPID1	Overshoot (%)	0	0	0	0
	Settling Time (s)	9.23	11.29	8.64	8.85
PID2	Overshoot (%)	-0.02	0.77	-0.02	-0.02
	Settling Time (s)	27.07	26.09	24.85	32.89
PID1	Overshoot (%)	-0.04	1.34	-0.02	-0.03
	Settling Time (s)	25.4	36.56	13.48	24.32

Concerning the comparison with the results obtained with the FPID1 and PID1 controllers developed in [10] where the Hyd/Oxy ratio is fixed at 1.145, so in this case, their control system employs only one manipulated variable. The simulation results data tabulated in Table 4 are clearly shows that the proposed controller FPID2 has a better control performance compared with the other considered controllers. Although the value of the overshoot of the FPID2 and FPID1 controllers kept at 0, the FPID2 controller exhibits a significantly shorter settling time compared to the FPID1 controller. While the control performance of PID1 and PID2 controllers remains very far from the control performance of the proposed FPID2 controller.

IV. CONCLUSION

In this paper, a novel adaptive fuzzy PID controller architecture has been formulated for the SOFC system, with the aim of enhancing the load tracking performance. This strategy ensures a constant output voltage at their reference value, a fuel utilization rate in a safe range and a Hyd/Oxy ratio around 1.145.

In summary, the proposed controller effectively addresses SOFC's nonlinearity, presenting a promising solution for the challenge of controlling SOFC's output voltage.

REFERENCES

1. Dicks A L, Rand D A J. Fuel cell systems explained. Third edition : Wiley; 2018. DOI:10.1002/9781118706992.
2. Williams M C, Quedenfeld H. Fuel cell handbook. Seventh edition : National energy technology laboratory, Morgantown, West Virginia; 2016.
3. Wang Y, Yoshib F, Watanabe T, Weng S. Numerical analysis of electrochemical characteris- tics and heat/ species transport for planar porous-electrode-supported SOFC. Journal of power source 2007; 170(1): 101-110. https://doi.org/10.1016/j.jpowsour.2007.04.004.
4. Gu J, Wang C, Lu W. Particle swarm PID control of solid oxide fuel cell. IEEE, the 2nd international conference on robotics, control and automation engineering, New York, United States 2019; 137-141. https://doi.org/10.1145/3372047.3372100.
5. Taher S A, Mansouri S. Optimal PI controller design for active power in grid-connected SOFC DG system. International journal of electrical power and energy systems 2014; 60: 268-274. https://doi.org/10.1016/j.ijepes.2014.02.010.
6. Darjat, Sulistyo, Triwiyatno A, Edwin Julia. Design of adaptive PID controller for fuel utilization in solid oxide fuel cell. International conference on information technology, computer and electrical engineering, Indonesia 2018; 234-239.
7. Kalyan C, Ravi S, Amit K. Fuzzy logic based controller for a grid-connected solid oxide fuel cell power plant. Journal of electrochemical energy conversion and storage 2014; 11(5): 51-59. https://doi.org/10.1115/1.4027709.
8. Ouagueni F. A new fuzzy control approach of the nonlinear solid-oxide fuel cell system. 1st International conference on sustainable energy and advanced materials, Ouargla, Algeria 2021.
9. Neethu M, Clint A, Shiny J, Sonsy H. Dynamic modelling and fuzzy control for solid oxide fuel cell (SOFC). International journal of advanced research in electrical, electronics and instrumentation engineering 2016; 5(6): 88-97. DOI 10.15662/IJAREEIE.20156.0506125.
10. Qin Y, Sun L, Hua Q, Liu P. A fuzzy adaptive PID controller design for fuel cell power plant. sustainability 2018;10(7):1-15. Doi 10.3390/su10072438.
11. Ji N, Xu D, Liu F. A novel adaptive neural network constrained control for solide oxide fuel cells via dynamic anti-windup. Neurocomputing 2016; 214:134.142. https://doi.org/10.1016/j.neucom.2016.05.076.
12. Hajimolana S, Hussain M, Natesan J, Tonekaboni S. Neural network predictive control of a tubular solid oxide fuel cell. Computer aided chemical engineering 2012; 3: 390-394.
13. Ouagueni F, Boumehraz M, Belhamdi S. A fuzzy model feed forward predictive control of the nonlinear tubular solid-oxide fuel cell system. Advances in modelling and analysis C 2019; 74(2-4): 71-79. https://doi.org/10.18280/ama_c.742-405.
14. Wu L, Wu X, Pan L, Shen J, Li Y, Zhang J. Fuzzy model predictive control of solide oxide fuel cell with zone traking. IFAC PapersOnLine 2019; 52(4): 210-215. https://doi.org/10.1016/j.ifacol.2019.08.180.
15. Shen D, Lim C C, Shi P. Robust fuzzy model predictive control for energy management systems in fuel cell vehicles. Control engineering practice 2020; 98: 1-12. https://doi.org/10.1016/j.conengprac.2020.104364.
16. Sun L Li, Shen J, Hua Q. Multiple model predictive hybrid feedforward control of fuel cell power generation system.

Sustainability 2018; 10(2):1-19. https://doi.org/10.3390/su10020437

17. Zhang T, Feng G. Rapid load following of an SOFC power system via stable fuzzy predictive tracking controller. IEEE Transactions on Fuzzy Systems 2009; 17(2): 357-371. DOI 10.1109/TFUZZ.2008.2011135
18. Wu J, Zhu J, Cao G, Tu H. Predictive control of SOFC based on a GA-RBF neural network model. Journal of power sources 2008; 179(1): 232-239. https://doi.org/10.1016/j.jpowsour.2007.12.036.
19. Swati S, Vijay K T, Hemender P S, Vinod K Y. Optimal design of fractional order PID controllers for solid oxide fuel cell system employing PSO algorithm. Aiub journal of science and engineering 2022; 21(1):7-16. https://doi.org/10.53799/ajse.v21i1.225.
20. Bo Y, Yulin L, Jiale L, Hongchun S, Xinyu Z, Yaxing R, Qiang L. Comprehensive summary of solid oxide fuel cell control: a state-of-the-art review. Protection and control of modern power Systems 2022; 36(7). https://doi.org/10.1186/s41601-022-00251-0.
21. Achenbach E. Response of a solid oxide fuel cell to load change. Journal of power sources 1995; 57(1-2): 105-109. https://doi.org/10.1016/0378-7753(95)02263-5.
22. Padulles J, Ault G W, McDonald J R. An integrated SOFC plant dynamic model for power systems simulation. Journal of power sources 2000; 86(1-2): 495–500. https://doi.org/10.1016/S0378-7753(99)00430-9.
23. T-Raissi A, Block D L. Hydrogen: automotive fuel of the future. IEEE power and energy magazine 2004; 2(6): 40-45.
24. Zhu Y, Tomsovic K. Development of models for analyzing the load-following performance of microturbines and fuel cells. Electric power system research 2002; 62(1):1-11. https://doi.org/10.1016/S0378-7796(02)00033-0.