Research Journal of Engineering & Technology. Vol., 1 (1), 39-52, 2024
Available online at http://www.rjetjournal.com
ISSN 2149-3340 ©2024

Optimizing Output Power and Stoichiometric Tracking Oxygen in PEM Fuel Cell System by Second Order Sliding Mode Controller with Super Twining Algorithm

Naghmeh Mirrashid[1], Seyed Mehdi RakhtAla[2*]

[1]Department of Electrical Engineering, Aliabad Katoul Branch, Islamic Azad University, Aliabad Katoul, Iran
[2]Assistant Professor, Department of Electrical Engineering, University of Golestan, Iran

[*]Corresponding Author Email: sm.rakhtala@gu.ac.ir

Abstract: This paper presents a cascade controller for controlling PEM fuel cell system. The purpose of control is to optimize net output of oxygen by keeping oxygen stoichiometry on favorite amount 2.5 and compressor power consumption is minimized. The controller system has been divided into two sections: internal ring and external ring. The external ring controls oxygen stoichiometric of second order sliding mode with super twining algorithm that its input is error of oxygen stoichiometric ratio. $w_{cp,ref}$ (Reference Compressor Airflow), the output of external ring, is reference of inner ring in compressor airflow controller. It produces inner ring of compressor voltage, v_{cm}, to apply in the fuel cell. In this paper, there has been used a fuel cell with complete nonlinear sixth order model that is a quite accurate and strongly nonlinear model. There has been prevented simplifying model and model reduction modes used in prior research. Using a system with six available and measurable modes by sensors are the model features including Motor Angular Velocity (ω_{cp}), Feed Manifold Pressure (P_{sm}), Db Rate of Feed Manifold (m_{sm}), Oxygen Pressure (P_{O2}), Nitrogen Pressure (P_{N2}) and Return Manifold Pressure (P_{rm}). The cascade controller based on the proposed super twining algorithm can tolerate on model uncertainties and disturbances consistency of the flow current properly. Simulation results show that in compared with classic single coil ring with super twining algorithm, the cascade controller with super twining algorithm has better transient performance in disturbances and applying uncertainties, and it is more favorable to reduce chattering and precise tracking.

Keywords: PEM fuel Cell, Second order sliding mode, Super twining algorithm, Cascade structure, Oxygen stoichiometry.

Introduction

Fuel cells are electrochemical devices that generate electrical energy from chemical materials continuously. They have a leading position in contemporary studies on renewable energy because of their high efficiency, renewability, low emissions, lack of environmental pollution and consumption of methanol, hydrogen and … as fuel. Compared to fossil fuels, they are being extensively developed in many power applications, due to high efficiency, fuel frequency (hydrogen and oxygen) in environment and lower emissions. However, function of the fuel cell face with some problems:

1. Oxygen starvation problem that is one of main factors to deteriorate the fuel cells;

2. Uncertainty of parameters, modeling error and uncertainty of modeling;
3. Dynamics' slow driving prevent stoichiometric rapid setting to prevent oxygen starvation;
4. Stack current is entered to control system as measurable disturbances. Stack current (I_{st}) enters a disturbance to the system that causes periodic and severe loss inλ_{o_2}. In other hand, compressor voltage (V_{cm}) affects variable λ_{o_2}indirectly.

It is clear that the system performance and efficiency is closely associated with the used type of control. This will justify studying options for improving the control fully. Reliable control systems to ensure stability and performance with straightness against uncertainties and external disturbance are importance for investment to achieve PEMFC success. In the past years, there have been suggested many control strategies for controlling operation of polymer fuel cells that each strategy has had its own objective(s) including air pressure control, compressor engine control, net power output control, stoichiometry-air ratio control, sensors' reduction etc. *Feedback-linearization*, *robust control*, *feedback* control, predictive control model, neural networks and sliding mode control are the most important control strategies. The provided control system for controlling oxygen stoichiometry in the literature can improve system efficiency and prevent irreversible damages in polymer membrane due to oxygen starvation phenomenon. There has been introduced designing airflow nonlinear control and its implementation of a fuel cell system in vitro as a new solution for problem of oxygen starvation, and the issue of control was solved by super twisting algorithms. Some of advantages of the proposed method are the ability system stability robust, convergence to sliding surface in limit time and reduce chattering even though uncertainty and turbulences of the model. In this work, there was firstly used the ability of the designed technique to fuel cell. The known model of fuel cell, PEM, was used in Pukrushpan. Kunusch (2011, 2013) used a second order strategy sliding mode by using super twisting algorithm to stabilize the system and prevent chattering phenomenon. Super twisting controller maintains features of distinctive stability of sliding mode twisting techniques, while providing a standard control signal smoother than what offers sliding mode. The main advantages of the adopted method by Kunusch are as follow:

- Solving problem of robust stabilizer for avoiding chattering effects;
- Increasing dynamic properties;
- Robustness to parameter uncertainties and external disturbances;
- Guarantying performance in a wide range, while highly nonlinear systems;
- Control Law depends to two measurable variables only (stack flow and compressor air dB), therefore, it does not require to monitor or state estimate.
- The algorithm structure is simple, therefore, requires less computation operation.

In addition, other important works have been published in recent years. There was applied a second order sliding mode control in cascade configuration to adjust oxygen dB in a 33 kW fuel cell stack. In the work, the reduced model is used to design the controller. Even experimental tests in are presented in Nami operation. Gabin (2010) studied implementing sliding mode on PEM fuel cell comprehensively. In this work, control law consist a feed forward section to offset effects of stack flow, enhance dynamic performance and response and improve transient response to flow changes; therefore, sliding mode control is used to control closed-loop. Using second order sliding mode control, Laghrouch suggested strategies that it may be achieved the better and transient response on stack fast-changing. He suggested the second order sliding mode control law based nonlinear optimization method to reduce chattering, stability in amount of excess oxygen and solving optimization problem of net power in fuel cells. He also proposed second order sliding mode control in cascade configuration with super twisting algorithm to improve output net power using maintain oxygen stoichiometric between 2-2.4, and used the reduced three-state model to design controller. In this article, we focus on ensuring maintain the desired oxygen stoichiometric value such that optimizing output net power.

The followings are some objectives of controlling objectives:

1. Preventing phenomenon of fuel starvation and increasing duration of stack life;
2. Minimizing power consumption of compressor;
3. Favorable interactions between compressor power and regulating oxygen stoichiometry

To improve performance and better control of fuel cell system, there has been used a six-state mode and more complex model instead the reduced three-state model of Laghrouch. The advantages of this model compared to the used model are better performance in operational range of fuel cell and lack of ignoring pressure dynamics. Moreover, the proposed controller has been measured by applying parametric uncertainty and current confusion in the cascade structure. It results have been compared with results of the proposed closed-loop controller. This paper is divided into the following chapters: In chapter 2, the model and its equations have been collected. Chapter 3 contains designing controller. Chapter 4 shows simulation results. Finally, chapter 5 includes conclusion.

Dynamical System and Control Objective

Hypotheses

The main hypotheses are as follows:

1. Anode pressure is constant; this can be accomplished by a separate control system;
2. Temperature and humidity are fix in stack input;
3. There is ignored dynamics of DC electric motor for driving compressor.

Nonlinear Dynamic Model of PEM Fuel Cell

Fig. 1 shows a schematic of fuel cell system with including stack with its accessories.

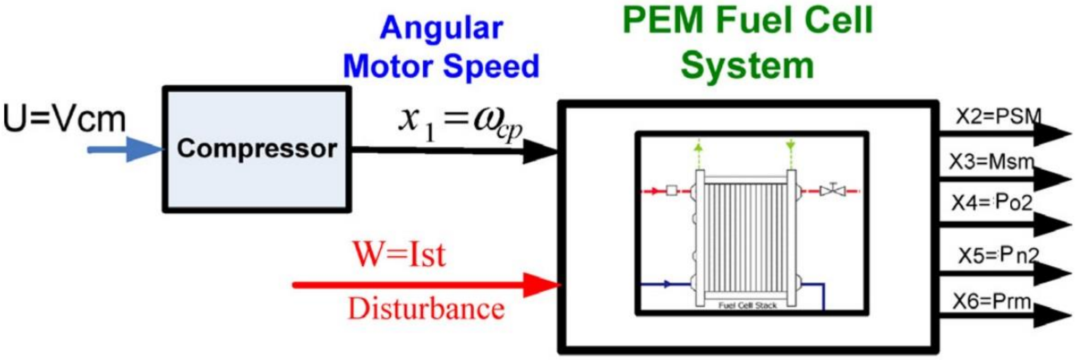


Figure 1. Block diagram of the fuel cell to provide model states.

The provided nonlinear dynamic model is similar that has been defined by the following six-state model with some changes: $x = \left[\omega_{cp}, P_{sm}, m_{sm}, P_{O_2}, P_{N_2}, P_{rm}\right]^T$. In which air consists only oxygen and nitrogen. The most significant amount of the gases in air is 79% and 21% for nitrogen and oxygen respectively.

Table 1. Defining states and parameters.

Parameters	Definition
Angular speed of electric motor	$x_1 = \omega_{cp}[rad/sec]$
Manifold pressure feed	$x_2 = P_{sm}[atm]$
Air mass in feed manifold	$x_3 = m_{sm}[kg]$
Oxygen pressure in cathode	$x_4 = P_{O2}[kg]$
Nitrogen pressure in cathode	$x_5 = P_{N2}[kg]$
Return manifold pressure	$x_6 = P_{rm}[atm]$

State Equations for the Proposed Model

Details of extracting the model have been expressed in details. Therefore, mode equations have been extracted with six variables that are shown in 1-6:

$$\dot{x}_1 = \tau_{cm} - \tau_{cp} = \frac{\eta_{cm}}{J_{cp}} \frac{k_t}{R_{cm}} (v_{cm} - k_v x_1) - \frac{\tau_{cp}}{J_{cp}} \tag{1}$$

$$\begin{aligned}\dot{x}_2 &= \frac{\gamma R_a}{V_{sm}} \left(-K_{sm,out} x_2 + K_{sm,out} P_{v,ca} + K_{sm,out} \frac{x_5}{M_{N2}} + K_{sm,out} \frac{x_4}{M_{O2}} \right) \frac{\gamma x_2}{x_3} + W_{cp} (T_{atm} \\ &\quad + \frac{T_{atm}}{\eta_{cp}} (\frac{x_2}{P_{atm}})^{\frac{\gamma-1}{\gamma}} - 1)\end{aligned} \tag{2}$$

$$\dot{x}_3 = W_{cp} - K_{sm,out} x_2 + K_{sm,out} P_{v,ca} + K_{sm,out} \frac{x_5}{M_{N2}} + K_{sm,out} \frac{x_4}{M_{O2}} \tag{3}$$

$$\begin{aligned}\dot{x}_4 &= -\frac{x_4 \; K_{ca,out}}{m_{O2} + m_{N2} + \frac{P_{v,ca} V_{ca} M_v}{R_v T_{st}}} \left(-x_6 + P_{v,ca} + \frac{x_5}{M_{N2}} + \frac{x_4}{M_{O2}} \right) y_{O2,in} K_{sm,out} \frac{(R_{O2} T_{st})}{V_{ca}} \left(x_2 - \frac{x_4}{M_{O2}} \right. \\ &\quad \left. - P_{v,ca} - \frac{x_5}{M_{N2}} \right) - n \frac{(R_{O2} T_{st})}{V_{ca}} \frac{M_{O2}}{4 \; F} I_{st}\end{aligned} \tag{4}$$

$$\dot{x}_5 = (1 - X_{O_2})(\,1 + \Omega_{atm})^{-1} K_{sm,out} \frac{R_{N2} T_{st}}{V_{ca}} \left(x_2 - \frac{x_4}{M_{O2}} - \frac{x_5}{M_{N2}} - P_{v,ca}\right) - \frac{x_5}{m_{O2} + m_{N2} + \frac{P_{v,ca} V_{ca} M_v}{R_v T_{st}}} K_{ca,out}\left(-x_6 + \frac{x_4}{M_{O2}} + \frac{x_5}{M_{N2}} + P_{v,ca}\right) \tag{5}$$

$$\dot{x}_6 = \frac{R_a T_{rm}}{V_{rm}} \left(K_{ca,out}\left(\frac{x_4}{M_{O2}} + \frac{x_5}{M_{N2}} + P_{v,ca} - x_6\right) - \left(P_{a_6} x_6^5 + P_{a_5} x_6^4 + P_{a_4} x_6^3 + P_{a_3} x_6^2 + P_{a_2} x_6 + P_{a_1}\right)\right) \tag{6}$$

In this model, compressor motor voltage ($u = v_{cm}$ [V]) and fuel cell stack current ($d = I_{st}$ [A]) are considered as system control input and measurable disturbance respectively. Table of parameters definition of the model contains the model parameters. Compressor output air flow rate ($W_{cp)}$ is:

$$W_{cp} = B_{00} + B_{10}(P_{sm}) + B_{20}(P_{sm})^2 B_{01}(\omega_{cp}) + B_{11} P_{sm} + \omega_{cp} + B_{02}(\omega_{cp})^2 \tag{7}$$

Output voltage is expressed as a function of stack current, reactant partial pressure, temperature of fuel cell and humidity of membrane. Standard potential of fuel cells will be decreased due to Ohmic losses, activation losses, voltage concentration losses. The actual output voltage of the fuel cell is difference between standard voltage and voltage losses in fuel cell, as which voltage losses are nonlinear functions of fuel cell current, temperature, pressure and chemical reactions of the fuel cell. Thermodynamic potential, E, is defined using Nernst equation in the developed form.

$$V_{fc} = E - losses \tag{8}$$

$$losses = V_{activation} + V_{ohmic} + V_{concentration}$$

$$E = N\left(E_0 + \frac{R\,T}{2\,F}\left\{\frac{P_{H2}\left(\frac{P_{O2}}{P_{OP}}\right)^{0.5}}{P_{H_2O_C}}\right\}\right) \tag{9}$$

So, it can be written:

$$v_{cell} = E - v_{act} - v_{ohm} - v_{conc} \tag{10}$$

$$v_{stack} = N\ v_{cell} \tag{11}$$

The linear control method will have problems optimal performance due to wide range disturbances. Therefore, using a PEM fuel cell nonlinear model, we should consider a nonlinear controller that guarantees more stability in large disturbances and is available in a wide range of modes.

Controller Design

Second Order Sliding Mode

Consider a nonlinear single-input:

$$\begin{aligned} \dot{x} &= f(x,t) + g(x,t)\,u \\ y &= s(x,t) \end{aligned} \tag{12}$$

$x \in x\complement R^n$ and $u \in U\complement R$ are state and input variables respectively, where

$$\begin{aligned} X &= \left\{x \in R^n \mid |x_i| \le x_{i,max}, 1 \le i \le n\right\} \\ U &= \{x \in R \mid |u| \le u_{max}\} \end{aligned} \tag{13}$$

f and g are the unknown functions.

Suppose control goal is to drive output function (x) (which is called sliding variable) to zero. It is assumed that the relative degree of the system is fixed. We assume that control directly appears from the first S derivation.

$$S = \frac{\delta}{\delta_x}[S][f(x) + g(x)u]$$

There are positive constants k_{M}, k_{m}, and C such that:

$$\forall\ u \in U\ ,\ \forall x \in X \qquad \left|\frac{\delta}{\delta_x} s\right| \le c \qquad 0 < K_m < \frac{\delta}{\delta_x}\dot{s} < K_M$$

Consider$[\zeta_1, \zeta_2]^T = [s, \dot{s}]^T$. Based on the previous definitions and conditions, the second order sliding mode will become to time stability under the following indefinite second order.

$$\begin{cases} \dot{\zeta}_1 = \zeta_2 \\ \dot{\zeta}_2 = a(x) + b(x)v \end{cases} \tag{14}$$

Where ζ_2 may be immeasurable. Referring to the previous point $v = u$ is input control. There are several algorithms to ensure the stability of the limited time in the system. Among them, super twisting algorithm has an integral on controller ring, so that the controller will be a continuous time function. The following control law defines this algorithm:

$$\begin{gathered} u = u_1 + u_2 \\ \dot{u}_1 = -\beta_s sign(s) \\ u_2 = \alpha_s |s|^{\frac{1}{2}} sign(s) \\ \alpha_s > 0 \quad ; \quad \beta_s > 0 \end{gathered} \tag{15}$$

With the following sufficient conditions that guarantee finite time convergence in the sliding manifold accordance Liapanov Function of fixed interest.

$$\beta_s > \frac{C}{K_m}\,, \qquad \alpha_s^2 \geq \frac{4CK_M(\beta_s + C)}{K_m^3(\beta_s - C)} \tag{16}$$

Designing and Controlling STW with the Fixed Interest

Equations 1-6 show dynamical equations of the simplified system. The second order sliding mode control technique is used to design a cascade structure that the diagram block in Fig. 2 shows it. This control method is a consistency against disturbances and parametric uncertainties.

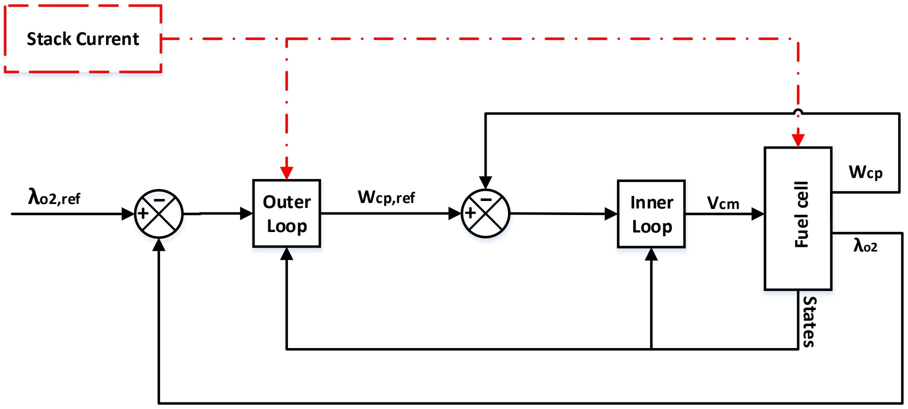


Figure 2. Schematic of control system with cascade structure.

The objective of control is to fix excess oxygen on 2.5. Controller system is divided into two parts: external ring and internal ring. External ring in controller excess oxygen ratio in 2-SMC includes super twisting algorithm with error of excess oxygen as input. Controller output, $w_{\mathrm{cp,ref}}$, is air compressor reference flux. This is a reference for internal ring in compressor air flux controller that generates compressor motor voltage,v_{cm}, to be applied in fuel cell. There have been selected two sliding manifolds to drive λ_{o_2} and w_{cp} to equilibrium points $\lambda_{o_{2,ref}}$ and$w_{\mathrm{cp,ref}}$.

External Ring

The sliding surface of external ring is defined as follows:

$$s_1 = \lambda_{O_2} - \lambda_{O_{2,ref}} \tag{17}$$

By derivative, we will have:

$$\dot{s}_1 = \dot{\lambda}_{O_2} = \frac{X_{O_{2,in}} \frac{1}{1+\Omega_{atm}} . K_{SM,OUT}}{\frac{nM_{O_2}}{4F} I_{st}} \left[\dot{x}_2 - \frac{\dot{x}_4}{M_{O_2}} - \frac{\dot{x}_5}{M_{N_2}} \right] \tag{18}$$

$$= A\ \frac{\gamma R_a T_{atm}}{V_{sm}}\left[1+\left(\left(\frac{x_2}{P_{atm}}\right)^4-1\right)n_{cp}^{-1}\right]W_{cp}$$
$$+ A\left[\frac{\gamma x_2}{x_3}(-x_2 B_{12}+B_{13}+\qquad B_{14}x_5+B_{15}x_4)-\frac{\dot{x_4}}{m_{O_2}}-\frac{\dot{x_5}}{m_{n_2}}\right]$$

Where

$$A=\frac{X_{O_{2,in}}\frac{1}{1+\Omega_{atm}}.K_{SM,OUT}}{\frac{nM_{O_2}}{4F}I_{st}}$$

It can be written:

$$\dot{s_1}=\dot{\lambda_{O_2}}=\gamma_1 W_{cp}+\phi_1 \tag{19}$$

Using linearization feedback technique, we will have:

$$W_{cp,ref}=\gamma_1(t,x)^{-1}\left(v_1-\phi_1(t,x)\right) \tag{20}$$

Where

$$\phi_1(t,x)=A\left[\frac{\gamma x_2}{x_3}(-x_2 B_{12}+B_{13}+B_{14}x_5+B_{15}x_4)-\frac{\dot{x_4}}{m_{O_2}}-\frac{\dot{x_5}}{m_{n_2}}\right] \tag{21}$$
$$\gamma_1(t,x)=\ \mathrm{A}\ \frac{\gamma \mathrm{R_a T_{atm}}}{\mathrm{V_{sm}}}\left[1+\left(\left(\frac{\mathrm{x_2}}{\mathrm{P_{atm}}}\right)^4-1\right)\mathrm{n_{cp}^{-1}}\right]$$

v_1 results to integral $\dot{S}_1=v_1$ that is designed for sustainability of the new system:

$$v_1=v_{11}+v_{12}$$
$$\dot{v_{11}}=-\beta_1 sign(s_1)\quad,\quad v_{12}=-\alpha_1|s_1|^{\frac{1}{2}}sign(s_1) \tag{22}$$

α_1 and β_1 are obtained according to the described terms in equation 16.

Internal Ring

Manifold of internal ring is defined as follows:

$$s_2=W_{cp}-W_{cp,ref} \tag{23}$$

Consider the first order derivative:

$$\dot{s}_2=\dot{W}_{cp}-\dot{W}_{cp,ref}$$

Therefore

$$\dot{W}_{cp}=[B_{10}+B_{11}x_{02}+2B_{02}x_1]\dot{x}_1+[B_{10}+2B_{20}x_2+B_{11}x_1]\dot{x}_2$$

Consider $D=[B_{10}+B_{11}x_{02}+2B_{02}x_1$. By replacing $\dot{x_1}$, we have:

$$\dot{W}_{cp}=DB_1K_1V_{cm}+D\left(-\left[\frac{c_p\times T_{atm}}{n_{cp}\times J_{cp}\times x_1}W_{cp}\left(\left(\frac{x_2}{P_{atm}}\right)^{B_4}-1\right)\right]+(-B_2x_1k_t)\right)+\qquad[B_{10}+2B_{20}x_2+B_{11}x_1]\dot{x_2}$$

Therefore:

$$\dot{s}_2=\phi_2(t,x)+\gamma_2(t,x)v_{cm}-\dot{W}_{cp,ref}$$
$$\gamma_2(t,x)=\frac{\partial s}{\partial v_{cm}}=\ DB_1K_1$$
$$\phi_2(t,x)=\frac{\partial s}{\partial x_2}\dot{x}_2+\frac{\partial s}{\partial x_1}\dot{x}_1\ D\left(-\left[\frac{c_p\times T_{atm}}{n_{cp}\times J_{cp}\times x_1}W_{cp}\left(\left(\frac{x_2}{P_{atm}}\right)^{B_4}-1\right)\right]+(-B_2x_1k_t)\right)+[B_{10}+2B_{20}x_2+B_{11}x_1]\dot{x_2} \tag{24}$$

Using linearization feedback technique:

$$v_{cm}=\gamma_2(t,x)^{-1}(v_2-\phi_2(t,x)+\dot{W}_{cp,ref}) \tag{25}$$

Where v_2 results to an integrator $\dot{s_2}=v_2$ that is designed for sustainability of the new system:

$$v_2=v_{21}+v_{22}$$
$$\dot{v}_{21}=-\beta_1 sign(s_2)\qquad,\quad v_{22}=-\alpha_2|s_2|^{\frac{1}{2}}sign(s_2) \tag{26}$$
$$\alpha_2=3\ ;\ \beta_2=2$$

α_2 and β_2 are obtained according to the described terms in equation 16.

Simulation Results

Applying Super Twisting Controller to Control Oxygen Stoichiometry

As the first attempt to improve system performance, we used a STW controller to control λ_{O_2}. Table 2 shows fluctuations of the system parameters that were used to apply parameter uncertainty.

Table 2. Fluctuations of the system parameters.

Fluctuations and uncertainties	Parameters
Stack temperature (T_{st})	+10%
Cathode volume (V_{ca})	+5%
Engine constant (k_{v})	-10%
Engine electrical resistance (R_{cm})	+5%
Compressor thickness or diameter (d_{c})	+1%
Engine inertia (J_{cp})	+10%
Atmospheric pressure (P_{atm})	+10%
Manifold source volume (V_{sm})	-10%
Return manifold volume (V_{rm})	-10%

The simulation results are as follow:

As seen in Fig. 3, all system states under the controller show desired behavior. Fig. 4 shows that λ_{O_2} will track optimal value $\lambda_{\mathrm{O}_2,\mathrm{ref}}$=2.5 properly and convergence time for conditions of applying uncertainty is 1 sec. Note that we must always avoid $\lambda_{O_2} < 1$ because impose many damages to fuel cell system. As previously mentioned, error relationships are as $S_1 = \lambda_{\mathrm{O}_2} - \lambda_{\mathrm{O}_2,\mathrm{ref}}$. According Fig. 6, net output power will be changed from 20-40 kW. According Fig. 5, control input or compressor motor voltage are 100-350 V.

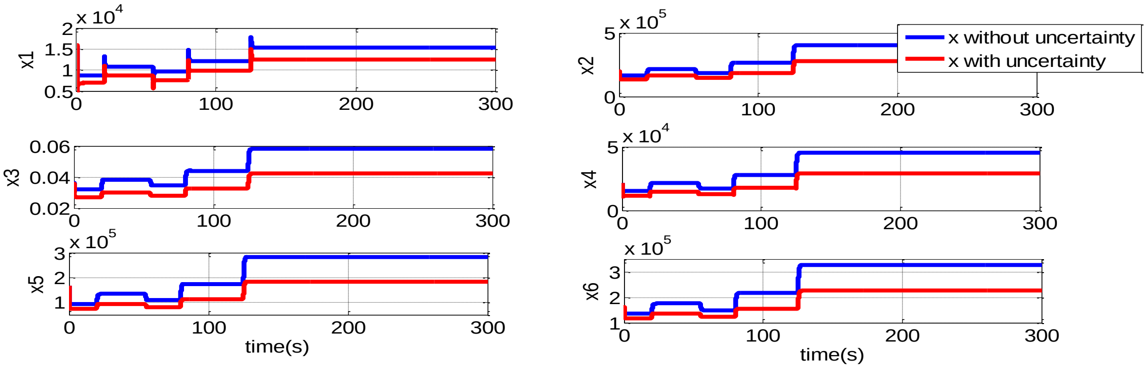


Figure 3. Modes' behaviour in conditions of applying super twisting controller on a class with disturbance input and uncertainty.

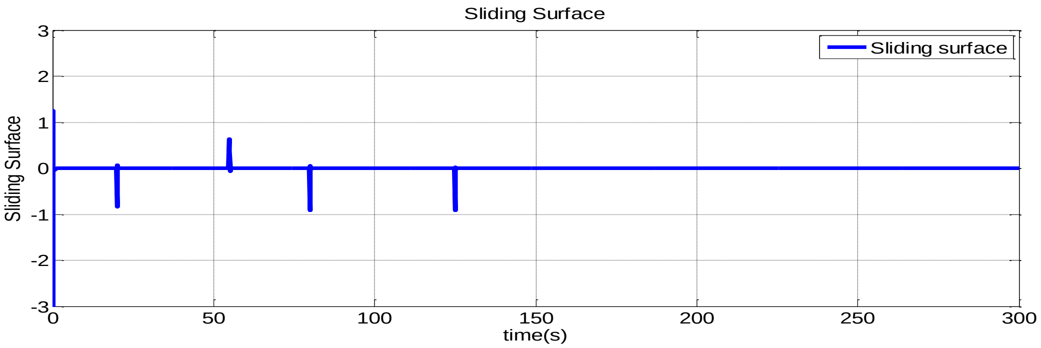


Figure 4. Sliding surface to control $\boldsymbol{\lambda_{O_2}}$

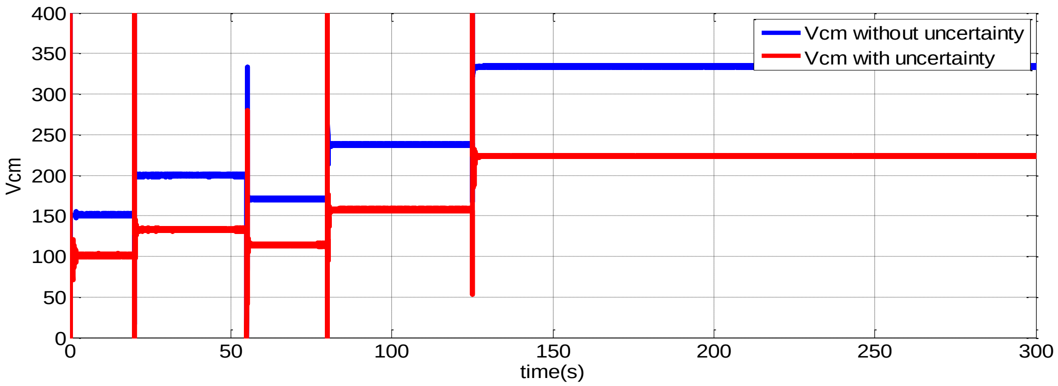


Figure 5. Control input in conditions of applying STW controller.

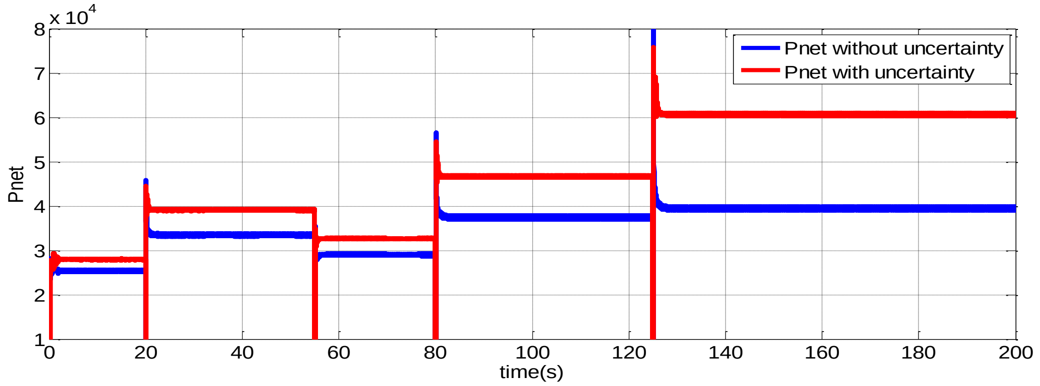


Figure 6. The net output power in mode of applying controller for $\boldsymbol{\lambda_{O_2}}$

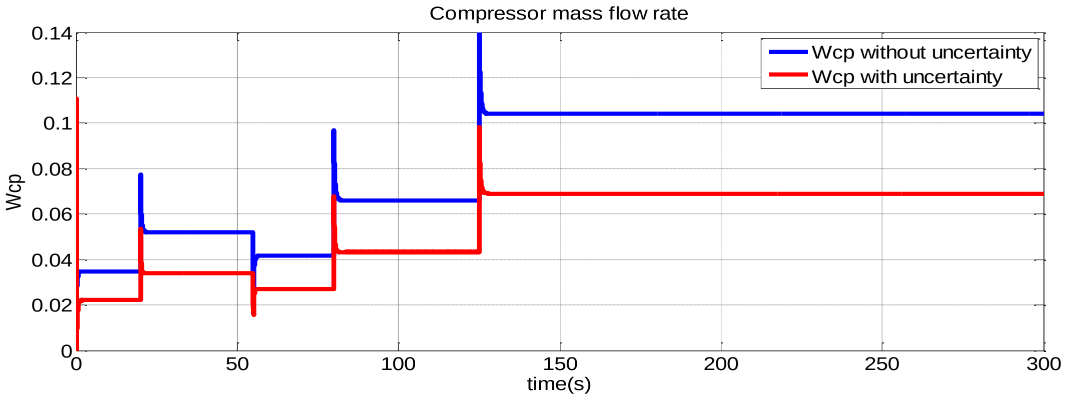


Figure 7. Compressor output airflow with parametric uncertainties.

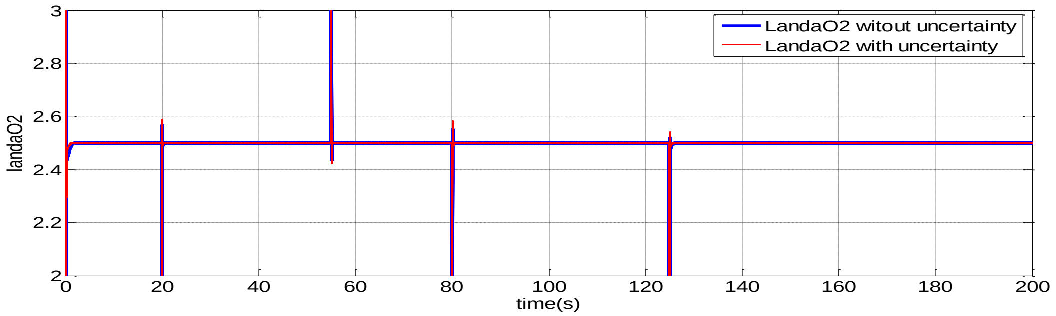


Figure 8. Oxygen stoichiometric with and without uncertainty.

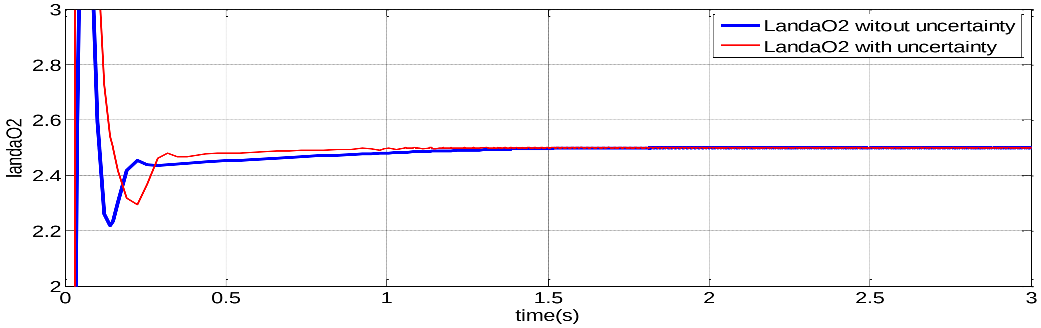


Figure 9. The convergence time of oxygen stoichiometry ration.

Applying Controller with Cascade Structure to Improve Net Output Power and Control Oxygen Stoichiometry

After applying super twisting simple controller and observing its results, we decided to design and implement the controller to achieve better performance of the system as cascade structure. As mentioned in the previous section, we obtained control laws, and finally the following turbulence output results were obtained by applying stack current. As seen in Fig. 10, systems under control the controller show proper behavior. Fig. 12 shows proper tracking λ_{O_2} in desired value $\lambda_{O_2,ref}$=2.5. Finite time convergence condition will be fulfilled according Fig. 13. t-values are 3 and 4 seconds for uncertainty and convergence time respectively. It is also avoided from $\lambda_{O_2} < 1$. As noted, S_1 is defined as tracking error of oxygen stoichiometry. According Fig. 14, net output power will be changed from 20-40 kW. According Fig. 11, control input or compressor motor voltage are 100-350 V.

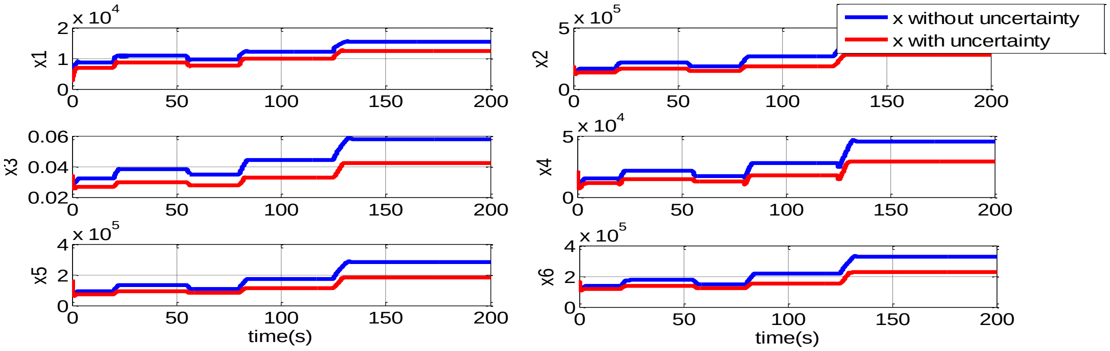


Figure 10. System modes' behaviour in conditions of applying cascade controller with disturbance and uncertainty.

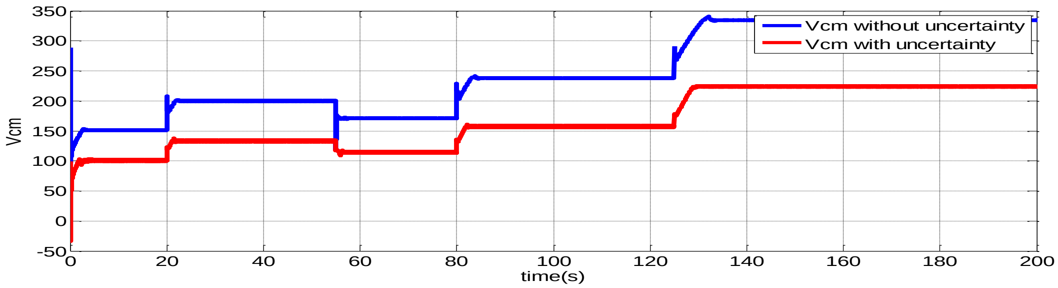


Figure 11. Control input to system (compressor motor voltage).

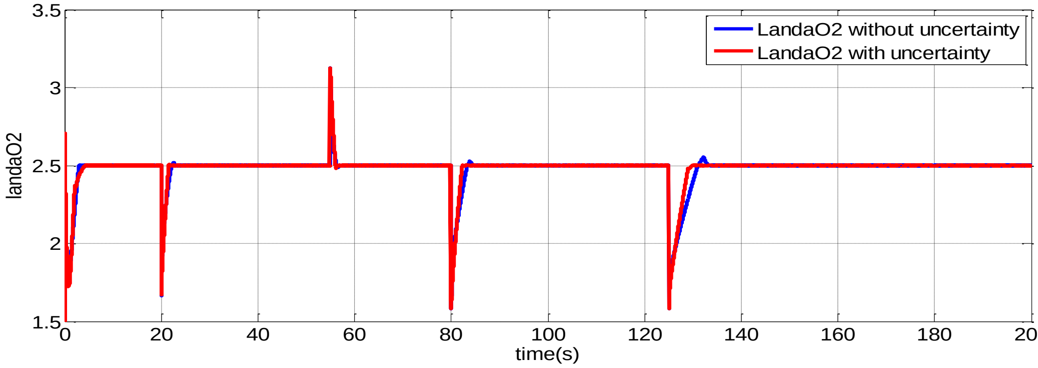


Figure 12. Oxygen stoichiometric conditions in conditions of applying cascade controller.

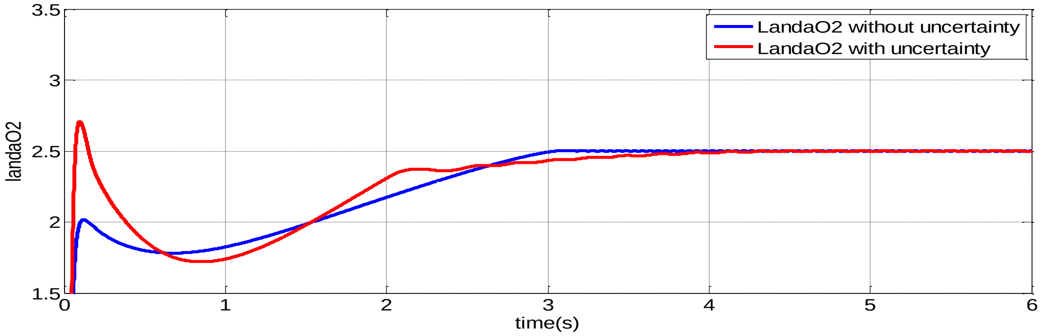


Figure 13. Convergence time of cascade structure.

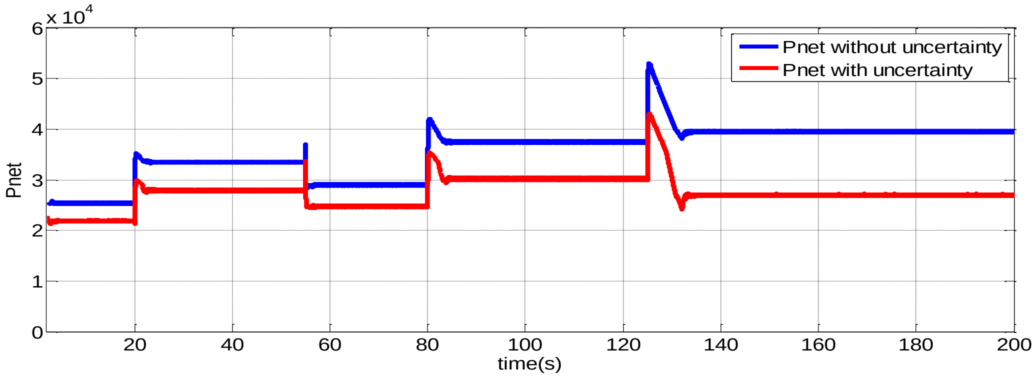


Figure 14. Net power output in conditions of applying cascade controller with input of disturbance.

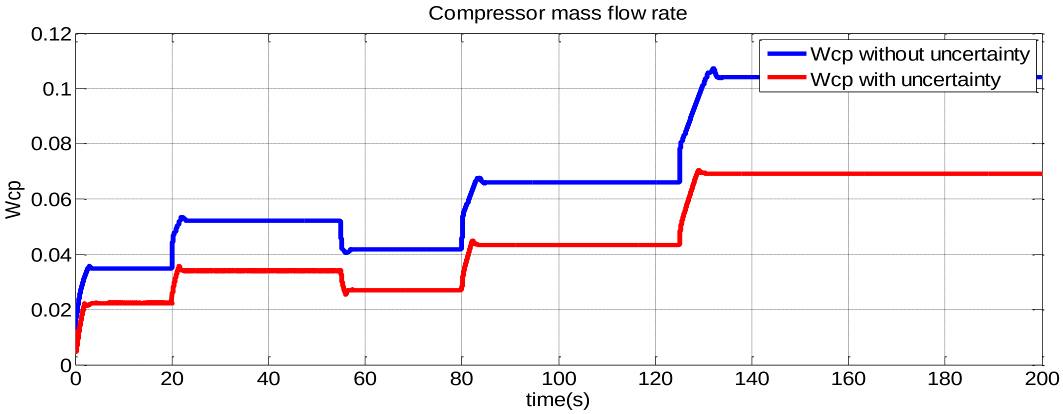


Figure 15. Compressor airflow in conditions of applying cascade controller with input of disturbance.

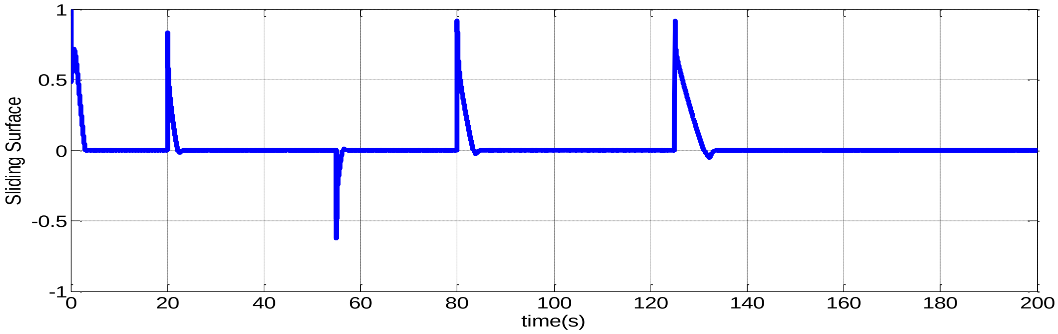


Figure 16. S1 sliding surface.

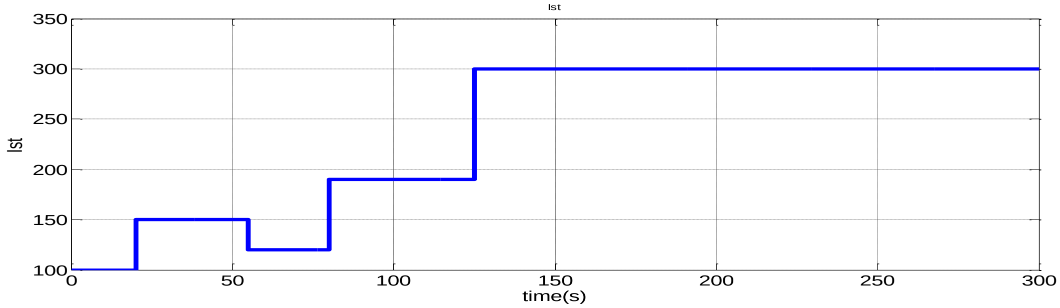


Figure 17. Disturbance input current.

The following controllers show the net power output.

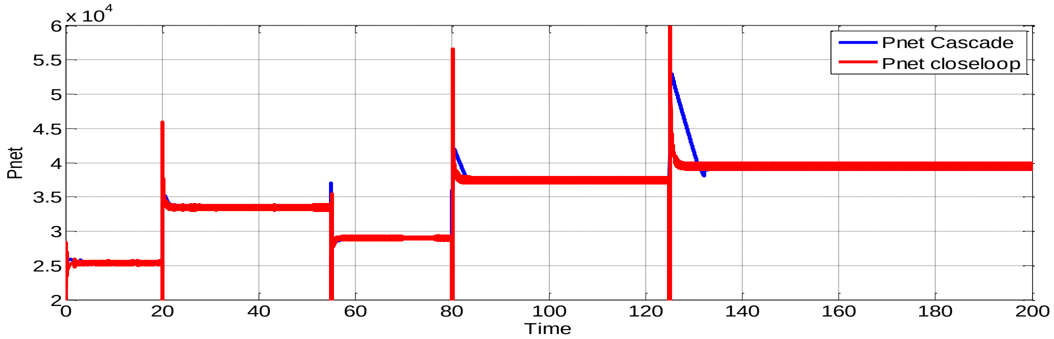
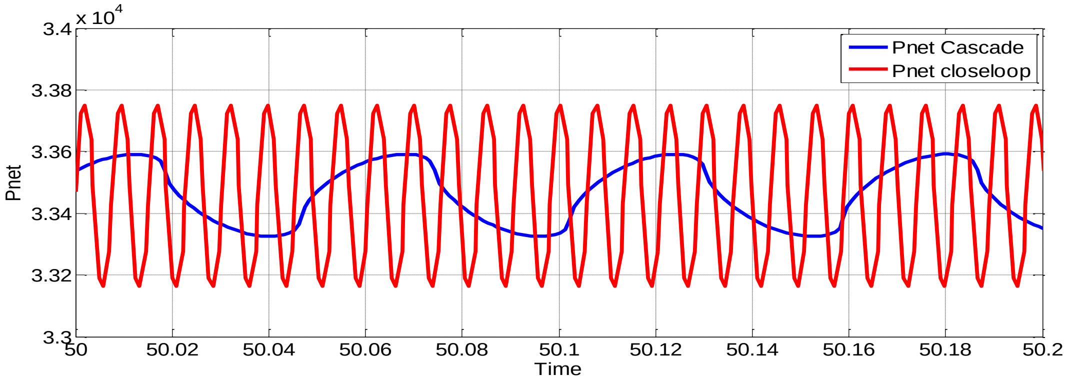


Figure 18. Comparing net power output in single-loop and cascade structures that can be observable by zoom in sec 50.



The following figures show chattering reduction in cascade controller with single-loop controller.

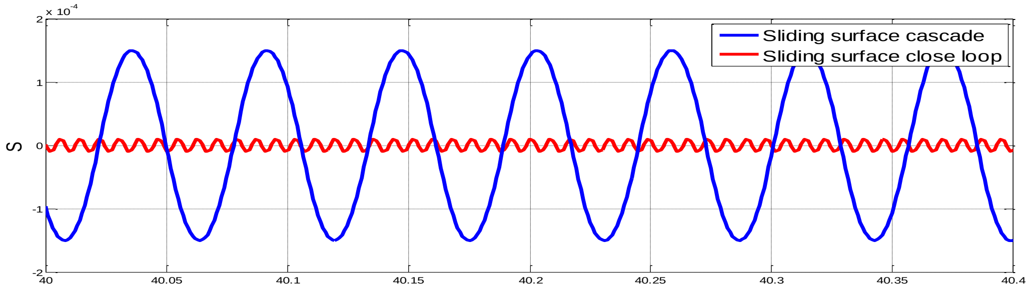


Figure 19. Comparing sliding surface of single-loop and cascade structures.

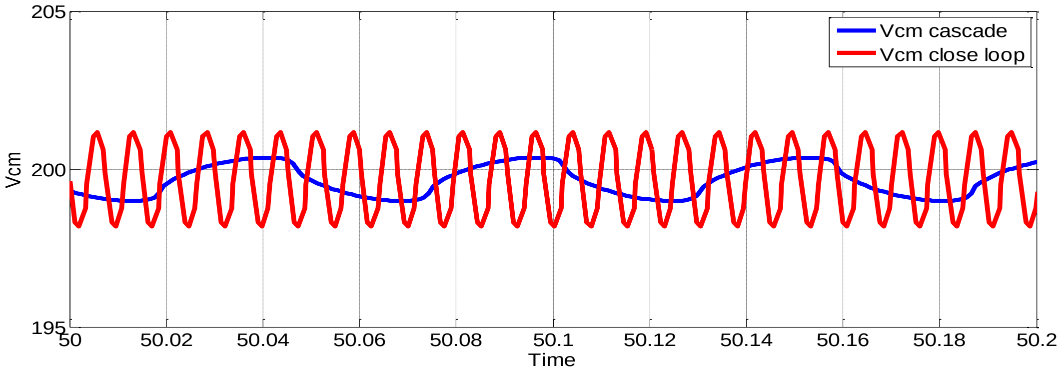


Figure 20. Comparing control input in single-loop and cascaded structures.

Conclusion

Fuel cell system technology provides numerous opportunities for nonlinear control. The system is highly nonlinear in nature and very complexity equations. Therefore, it can be more developed to achieve the best performance and results. The present research focused on high order sliding mode controller based on super twisting algorithm to control and improve performance of fuel cell system. Twisting controllers were provided and designed in two forms: single-loop and cascade structures. Then they were tested through several simulations, despite turbulence and uncertainty of parameter. This design method requires finding a bound for disturbances and uncertainty. Finally, the obtained bounds were used to calculate the fixed interest with design parameters. It forced oxygen stoichiometry to track the desired value 2.5. It also improved net output power. We also indicated that we can achieve a correct and resistance behavior to track maximizing output net power by designing high order sliding controllers. Chattering has been also substantially reduced.

Table 3. Comparing results.

Parameters	Closed loop controller	Cascade controller
Net output power	25-40 kW	25-40 kW
Installing oxygen stoichiometric	2.5	2.5
Convergence time	1.5 s	3 s
Controller input	150-350 V	150-350 V
Compressor air flow	0.03-0.11	0.03-0.11

References

Almeida PE, Simoes MG, 2005. Neural optimal control of PEM fuel cells with parametric CMAC networks. Industry Applications. IEEE Transactions. 41(1): 237-245. [Google Scholar] [Publisher] https://doi.org/10.1109/IAS.2003.1257600

Bordons C, Arce A, Del Real A, 2006. Constrained predictive control strategies for PEM fuel cells. American Control Conference. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/ACC.2006.1656595

Evangelista C, 2010. Variable gains super-twisting control for wind energy conversion optimization. Variable Structure Systems (VSS). 11th International Workshop. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/VSS.2010.5544713

Garcia-Gabin W, Dorado F, Bordons C, 2010. Real-time implementation of a sliding mode controller for air supply on a PEM fuel cell. Journal of Process Control. 20(3): 325-336. [Google Scholar] [Publisher] https://doi.org/10.1016/j.jprocont.2009.11.006

Gruber JK, Bordons C, Dorado F, 2005. Nonlinear control of the air feed of a fuel cell. American Control Conference. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/ACC.2008.4586643

Grujicic M, Chittajallu K, Pukrushpan J, 2004. Control of the transient behaviour of polymer electrolyte membrane fuel cell systems. Proceedings of the Institution of Mechanical Engineers. Part D. Journal of Automobile Engineering. 218(11): 1239-1250. [Google Scholar] [Publisher] https://doi.org/10.1243/0954407042580039

Harmouche M, 2012. Homogeneous higher order sliding mode control for PEM fuel cell. Variable Structure Systems (VSS). 12th International Workshop. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/VSS.2012.6163495

Kunusch C, 2009. Sliding mode strategy for PEM fuel cells stacks breathing control using a super-twisting algorithm. Control Systems Technology. IEEE Transactions. 17(1): 167-174. [Google Scholar] [Publisher] https://doi.org/10.1109/TCST.2008.922504

Kunusch C, 2010. Efficiency optimisation of an experimental PEM fuel cell system via super twisting control. Variable Structure Systems (VSS). 11th International Workshop. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/VSS.2010.5544677

Kunusch C, 2013. Experimental results applying second order sliding mode control to a PEM fuel cell based system. Control Engineering Practice. 21(5): 719-726. [Google Scholar] [Publisher] https://doi.org/10.1016/j.conengprac.2012.08.002

Li Q, 2009. Nonlinear robust control of proton exchange membrane fuel cell by state feedback exact linearization. Journal of Power Sources. 194(1): 338-348. [Google Scholar] [Publisher] https://doi.org/10.1016/j.jpowsour.2009.04.077

Liu J, Laghrouche S, Wack M, 2013. Differential flatness-based observer design for a PEM fuel cell using adaptive-gain sliding mode differentiators. Control Conference (ECC). European. IEEE. [Google Scholar] [Publisher] https://doi.org/10.23919/ECC.2013.6669475

Matraji I, 2012. Adaptive second order sliding mode control of PEM fuel cell air feed system. CDC. [Google Scholar] [Publisher] https://doi.org/10.1109/CDC.2012.6426468

Matraji I, 2012. Extremum seeking control for net power output maximization of a PEM fuel cell using second order sliding mode. Variable Structure Systems (VSS). 12th International Workshop. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/VSS.2012.6163524

Matraji I, 2013. Robust control of the PEM fuel cell air-feed system via sub-optimal second order sliding mode. Applied Energy. 104: 945-957. [Google Scholar] [Publisher] https://doi.org/10.1016/j.apenergy.2012.12.012

Matraji I, Laghrouche S, Wack M, 2011. Cascade control of the moto-compressor of a PEM fuel cell via second order sliding mode. Decision and Control and European Control Conference (CDC-ECC). 50th IEEE Conference on 2011. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/CDC.2011.6161412

Na WK, Gou B, 2008. Feedback-linearization-based nonlinear control for PEM fuel cells. Energy Conversion. IEEE Transactions. 23(1): 179-190. [Google Scholar] [Publisher] https://doi.org/10.1109/TEC.2007.914160

Nehrir MH, Wang C, Shaw SR, 2006. Fuel cells: Promising devices for distributed generation. Power and Energy Magazine. IEEE. 4(1): 47-53. [Google Scholar] [Publisher] https://doi.org/10.1109/MPAE.2006.1578531

Pukrushpan JT, Stefanopoulou AG, Peng H, 2004. Control of fuel cell power systems: Principles, modeling, analysis and feedback design. Springer. [Google Scholar] [Publisher]

Rakhtala SM, 2014. Design of finite-time high-order sliding mode state observer: A practical insight to PEM fuel cell system. Journal of Process Control. 24(1): 203-224. [Google Scholar] [Publisher] https://doi.org/10.1016/j.jprocont.2013.08.006

Talj R, 2009. A reduced-order model and a higher-order sliding-mode control of the air supply system of a proton-exchange-membrane fuel cell with experimental validation. Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium. ELECTROMOTION 2009. 8th International Symposium on 2009. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/ELECTROMOTION.2009.5259134

Talj R, Hilairet M, Ortega R, 2009. Second order sliding mode control of the moto-compressor of a PEM fuel cell air feeding system with experimental validation. Industrial Electronics. IECON'09. 35th Annual Conference of IEEE. IEEE. [Google Scholar] [Publisher] https://doi.org/10.1109/IECON.2009.5415414

Talj RJ, 2010. Experimental validation of a PEM fuel-cell reduced-order model and a moto-compressor higher order sliding-mode control. Industrial Electronics. IEEE Transactions. 57(6): 1906-1913. [Google Scholar] [Publisher] https://doi.org/10.1109/TIE.2009.2029588