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Research Paper

Fuel Cell Systems and Developments in Control Abilities

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Abstract
Due to the oil depletion as well as air pollution, new and renewable energies are a highly considered subject in studies and experiments of few recent decades. Among various renewable energy sources, are most noticed due to led environmental pollution and high efficiency. Clearly, the optimal performance of the system depends on the type of the applied controller. This study reviews control techniques used for fuel cell systems. The results of applying different controllers on the system are studied then better control techniques are introduced. The problems involved in fuel cell systems as well as the advantages and disadvantages of different applied control techniques are specified.

Keywords: PEM Fuel cell, Second order sliding mode, super twisting algorithm, Cascade structure, stoichiometry of oxygen.

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Introduction

Fossil fuels are non-renewable energy sources and it is essential to find a proper, cheap and clean alternative for it. The energy crisis between 1973 and 1991 and the increasing environmental pollution persuaded the industrial countries to substantially invest on environment-friendly and high efficiency systems.

Due to the high efficiency, being renewable, lower emissions thus less polluting the environment as well as using methanol, hydrogen and so on as fuel, fuel cells are specifically considered in recent researches on renewable energies (Matraji, Ahmed, Laghrouche, & Wack, 2012). The fuel cell converts chemical energy into electrical energy so that the cell components including cathode, anode and electrolyte are not consumed. This conversion is a reaction reverse to electrolysis of water; in other words, the reaction between hydrogen and oxygen produces water, heat and electricity. Fuel cell is like a battery; however, unlike the battery, it does not need charging and the system will work as long as the required air and fuel are supplied for the cell.

There are several types of fuel cell systems. Here, the PEM (Proton Exchange Membrane) fuel cell is studied. In PEM fuel cell, hydrogen is used as the anode fuel.

Depending on the type and arrangement of the system, the electrical efficiency of the fuel cell ranges from 36% to 60% than can increase to 85% employing common heat recovery equipment. PEM fuel cell performance depends on a variety of factors including: hydrogen and oxygen partial pressure, stack temperature, and humidity of the membrane.

Fuel cells will play an important role in reducing environmental pollution and due to having few mechanical parts, no noise is generated. In addition, the fuel cell system efficiency is relatively high compared to internal combustion engines (Chowdhury & Crossley, 2009), has no noise and

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vibration, and needs low maintenance. These make fuel cell suitable for use in the city and suburbs.

Fuel cell problems

Oxygen starvation

In the fuel cell, if reactant are consumed faster than they can be supplied, the fuel starvation phenomenon will occur (Matraji, Laghrouche, & Wack, 2011). Hydrogen and oxygen partial pressure deficiency during pulling the stack current causes a severe drop in stack-voltage then resulting in high current density. Lack of reactive will lead to fuel or oxygen starvation that destroys the fuel cell materials. Due to non-uniform distribution of current density within the cell, spot (local) burn occurs, causing damage to the membrane and the catalyst layers. This causes a hot spot on the membrane. If the reactant in the fuel cell is consumed faster than they can be supplied, the fuel starvation phenomenon will occur. This phenomenon occurs in transient state and is major causes of depreciation and obsolescence of fuel cells.

The uncertainty of parameters, the error caused by modeling and the uncertainty in the modeling

Having a structure with parametric uncertainties and external disturbances as well as a highly non-linear nature, the system is required to have a suitable for controller ensuring a wide range of performances. Linear control techniques and linearization around several operating point are not appropriate for such systems.

The actuator slow dynamics

This prevents rapid adjustment of the air stoichiometric ratio to avoid oxygen starvation. In air flow control, stoichiometry must be controlled quickly, efficiently, stable and consistently (Garcia-Gabin, Dorado, & Bordons, 2010; Grujicic, Chittajallu, & Pukrushpan, 2004; Pukrushpan, Stefanopoulou, & Peng, 2004a; R. Talj, Hissel, Ortega, Becherif, & Hilairet, 2009; R. J. Talj, Hissel, Ortega, Becherif, & Hilairet, 2010). In fuel cell system control, the slow dynamics of actuators (electric motor or PMSM (Permanent Magnet Synchronous Motor) with compressor) avoid quickly regulating the stoichiometry of oxygen (λ_{o2}) to prevent oxygen starvation. Especially during rapid changes in current, in risk of starvation increases. Therefore λ_{o2} regulation is a critical issue.

Stack current as measurable disturbances enters the control system

Stack current (Ist) enters a disturbance into the system which has a direct and immediate impact on the performance of the fuel cell and makes an instantaneous and intense drop in λ_{o2}. On the other hand, the compressor voltage (V_{cm}) indirectly affects λ_{o2}. Indeed, the high rate of λ_{o2} increases the oxygen partial pressure and improves the stack power P_{st}. However, λ_{o2} increment is consistent with the high power demand of compressor and increases the losses. Therefore, regulation of the air flowing in the cathode during current fluctuations helps achieving control objectives.

In applications associated with power systems, vehicles, and unmanned aerial vehicles, the fuel cell are usually installed close to the stack and often experience periodic and large disturbances due to the continuous changes in stack (Chowdhury & Crossley, 2009; Kunusch, Puleston, Mayosky, & Dávila, 2010). Thus, it is essential to provide a suitable nonlinear controller ensuring a more stable performance against large disturbances and in a wide range of conditions. Parametric uncertainties, external disturbances, and the nonlinear nature of the system require a suitable controller to be designed to ensure a good transient performance under stack changes and parametric uncertainties. High cost, low reliability and short lifetime are still fuel cell limits in in industrial applications. Therefore, an improved control system for costs reduction, rapid dynamic response, long life and energy efficiency is essential. Therefore, a control objective is a good interaction between the two following objectives:

1. Avoiding fuel starvation phenomenon, regulated stoichiometry of oxygen and increased stack life-time;
2. Minimizing (optimizing) the compressor power consumption.

Control techniques applied on fuel cell systems and the objectives

In recent years, many control strategies have been suggested for controlling the performance of PEM fuel cells that each follows specific objective. Objectives may be controlling the pressure difference, compressor engine, the net output power, stoichiometric air ratio, and reducing the number of sensors (Liu, Laghrouche, & Wack, 2013). Among control strategies we can mention the feedback linearization (Na & Gou, 2008; Pukrushpan, Stefanopoulou, & Peng, 2004b), the robust control strategy (Li, Chen, Wang, Jia, & Han, 2009), feedforward control (Pukrushpan et al., 2004a) and predictive control model (Bordons, Arce, & Del Real, 2006; J. K. Gruber, Bordons, & Dorado, 2008), neural networks (Almeida & Simoes, 2005), and various sliding mode control (Garcia-Gabin et al., 2010; R. Talj, Hilairet, & Ortega, 2009; R. Talj, Hissel, et al., 2009). The feedback linearization method converts the nonlinear dynamics to the linear one and employs the linear control method (error tracking) to design an optimal controller. Although this method can improve the transient response of the system as well as the fast response to changes in stack current, it requires a detailed knowledge on some parameters. On the other hand, if there is parametric uncertainty or un-modeled dynamics, this method does not guarantee the robustness. In feedback-based feedforward control, due to unexpected disturbances, the stability of the system cannot be guaranteed. Although, the technique reduces the sensitivity of the system to the parametric uncertainty. Bordon predictive control model (Bordons et al., 2006; J. Gruber, Doll, & Bordons, 2009; J. K. Gruber et al., 2008) tries to achieve various operational objectives. Bordon considered three different control measures including tracking the target output voltage, avoiding fuel starvation, and maximizing the fuel efficiency. To fulfill these objectives, the GPC (Generalized Predictive Control) algorithm was employed. Recently, a limited MPC strategy has been applied on a real fuel cell (J. Gruber et al., 2009). The results obtained from the NN-based techniques (Almeida & Simoes, 2005) indicates the practical advantage of this technique compared to the conventional PID. In particular, the desired results of optimized NN-based techniques include automatic adjustment, control objective selection, excellent adaptability, flexibility, good consistency and stability.

Sliding-mode-based control techniques

Sliding mode control

The best technique to control the fuel cell system is the sliding mode control. Sliding mode control technique is adapted from variable-structure control system. This type of controller is applicable for a wide class of systems with high nonlinearity, modeling errors, disturbances, uncertainties and time-varying system. Due to the complex dynamics and highly nonlinear model, fuel cell control is considered as a great challenge. Hydrogen-air fuel cell system is a high-order nonlinear model. Therefore, to have an effective controller, it is essential to apply techniques copping with internal and external disturbances as well as uncertainties in the fuel cell system. Sliding mode control is a control technique suitable for changing-structure systems. It is a robust method for controlling uncertainties, and internal and external disturbances. Sliding mode is movement on a discontinuous set of a dynamical system so that the control signal is a signal with infinite switching frequency. Sliding mode control defines a time-varying level S(t) in the state space. The sliding level is considered as s = 0. After applying the high-frequency control signal, states can be guided to then kept at the sliding level. Thus, the system is consistent against uncertainties and disturbances. The standard sliding mode (1st order) uses the sign function for control signal making the signal nonlinear and discontinuous and causing the control signal swing near the sliding level. This makes the control signal having a high switching frequency causing vibration effects that leads to problems consequently. In the fuel cell, high-frequency switching leads to degradation actuators. To fix the problems involved in the sliding mode, a new technique called high-order sliding mode is recently introduced. This control signal at a high switching frequency and vibration effects that problems will follow. The fuel cell triggers the switching frequency leads to destruction. Recently, a new approach to solving the problem of sliding mode called high-order sliding mode is provided. Algorithms belonging to the family of high-order sliding mode (HOSM) are suitable and attractive choices. They can provide stability and robustness to nonlinear systems; converge to the reference in a limited time, thus avoiding the effects of vibration. HOSM lacks disadvantages of sliding mode control including vibration. Since second-order sliding mode (SOSM) algorithm is a HOSM, it can be an excellent choice for nonlinear uncertain systems. Since the sliding variable is a function of the relative degree with the control factor u(t), the discontinuous control by SOSM is a time derivation of $\dot{u}$ (t) provided for $\sigma = \dot{\sigma} = 0$ with a continuous u (t). As a result, the chattering phenomenon is alleviated. Obviously, proper performance and efficiency of the system is closely related to the type of applied control. This justifies the study on options for improving the control (C Evangelista, Puleston, Valenciaga, & Dávila, 2010).It is important to invest on reliable control systems ensuring the consistency and sustainability against model uncertainties and external disturbance to succeed in PEMFC (Kunusch, Puleston, Mayosky, & Fridman, 2013).

A powerful algorithm in SOSM is super twisting algorithm (STW) appropriate for systems with relative degree of one. This continuous control function directs the sliding (error) level and the derivatives to zero in a finite time in the presence of disturbances with limited bandwidth. Since STW algorithm consists of a discrete function in the integral, chattering is not totally removed but weakened. The main drawback in STW control algorithm is the need to detailed information on the range of disturbance which cannot easily be specified in many practical applications. When designing the STW control principles, disturbance range should be considered larger than the required gain control.

A simple comparative-based technique is proposed to regulate SESM to deal with the uncertainty of the system. The main advantage of comparative-based SESM controller is that it does not require a detailed knowledge on the upper boundary of the system uncertainty. It is also expected the propose controller have a better tracking performance even in the presence of external disturbances with less efforts.

Application, objectives, advantages and disadvantages of sliding mode in fuel cell control

Sliding mode control system proposed in (C Evangelista et al., 2010; Garcia-Gabin et al., 2010; Harmouche, Matraji, Laghrouche, & El-Bagdouri, 2012; Pukrushpan et al., 2004b; Slotine & Li, 1991) to control the stoichiometry of oxygen can improve system efficiency and prevent irreversible damage to the polymer membrane due to oxygen starvation. As a new solution to the problem of oxygen starvation, air flow nonlinear control was introduced and implemented in a laboratory fuel cell system (Slotine & Li, 1991). Thus, super twisting algorithm (STA) solved the control problem. Advantages of the proposed control technique include the robustness of the system, the convergence to the sliding level in a finite time, and chattering alleviation even with uncertainties and disturbances. In the research conducted by Kunusch in 2009, this technique was first applied to the fuel cell (Kunusch et al., 2013). Kunusch in 2010 (Kunusch et al., 2010) employed SOSM strategy using STA (Super Twisting Algorithm) to stabilize the system and prevent chattering phenomenon. Super twisting controller have the distinct consistency features of sliding mode techniques while providing a control signal smoother than that the standard sliding mode provides. The main advantages of the method adopted by Kunusch are as follows:

- Solving the problem of a robust stabilizer for avoiding the effects of chattering;
- Improving the dynamic properties;
- Robustness to parametric uncertainties and external disturbances;
- Ensuring a good performance in a wide range despite the highly nonlinear nature of the systems;
- Dependence of control principle on two measurable variables (the stack current and compressor air flow) thus no needing to state estimator or monitor.
- Simple algorithm structure thus requiring less computation.

In addition, important studies have also been published in recent years. In (R. J. Talj et al., 2010), SOSM control in cascade configuration is applied to adjust the oxygen flow rate on a 33 kW fuel cell stack. This study employed the order reduction model and changes in the system model to design the controller. Experiments on named performance were also presented. Gabin (2010) conducted a comprehensive study on implementation of sliding mode on PEM fuel cell. Here, the control principle includes a feedforward part to compensate for the effects of the stack current and to enhance the performance of the dynamic response as well as to improved transient response to changes in stack current. Sliding mode control is also used in a closed loop control. Employing SOSM control, Laghrouch (Harmouche et al., 2012; Matraji et al., 2012; Matraji et al., 2011) suggested strategies with better performance and transient response against rapidly changing stack. In (Matraji et al., 2012), he proposed a nonlinear SOSM control principle based on optimized extreme searching method to reduce chattering, to provide stability in excess oxygen rate, and to solve optimization problem for fuel cell net power. In (Matraji et al., 2011), he suggested a SOSM in Cascode configuration with STA to improve the output net power by maintaining the stoichiometric oxygen rate between 2 and 4.2 consisting of two outer and inner loop. The outer control loop controls the stoichiometric air rate through a SOSM and feedback linearization. The outer loops control the compressor voltage. Here, a reduced-order model is employed to design the controller. There are some other valuable works about fuel cell control including the Zenith and Skogestad (Zenith & Skogestad, 2007). This paper analyzes the output power control when a DC/DC converter is employed to connect the fuel cell to the stack. This study mainly focused on fuel cell output power control and it assumed that the control of reaction is ensured by controlling sub-systems. In this paper, the system was composed of a fuel cell, compressor, valves, and DC/DC converters. Evangelista in 2010 (C Evangelista et al., 2010) and 2013 (Carolina Evangelista, Puleston, Valenciaga, & Fridman, 2013) employed variable-gain sliding mode control to optimize the conversion of wind energy. He obtained desired results such as consistency against internal and external disturbances as well as the uncertainty of the model, accurate regulation and tracking of variables while converging in a finite time. Comparing the proposed method to the standard sliding mode strategy, he concluded that this technique reduced mechanical stresses as much as possible (prevention of mechanical erosion) while reducing the output chattering. Gonzalez (2012) (Gonzalez, Moreno, & Fridman, 2012), proposing a new technique for calculating the disturbance bounds, implemented variable gain control technique on a spring-mass system. Comparing classical STA, first order sliding mode, and modified STA by apply them to the system, he concluded that the control first order sliding mode shows a little chattering which is substantially decreased by both constant-gain STA and variable-gain STA. Compared to classical STA, the variable-gain STA to compensate for the larger class of perturbations and further reduce the chattering effect.

Due to novelty, this algorithm has few practical applications; however, it has theoretically notable progress. Studying the lyapunov stability theory, in (Dávila, Moreno, & Fridman, 2010; Gonzalez et al., 2012; Moreno, 2012) the variable-gains were extracted and a finite time convergence was achieved by the algorithm. Examining the proposed strategy, we find that it is valuable to work and research on this technique for fuel cell system.

Conclusion

As discussed earlier, because of the highly nonlinear nature of the fuel cell system and parametric uncertainties, much work must be done to achieve the desired results. Considering the mentioned process and according to the obtained results, high order sliding mode control algorithms are interesting for researchers for future works. This technique ensures the robustness against parametric uncertainties and external disturbances as well as the optimal performance of the systems in a wide range despite the highly nonlinear nature of the system. The control principle is also easier and depends only on two measurable variables; therefore, state estimator or monitor is not required. The algorithm structure is simple thus not much computation is required. Due to the novelty, there is a good potential to conduct new researches on Evangelista technique for fuel cell system control.

References

Almeida, EM P, Simoes, 2005. Neural optimal control of PEM fuel cells with parametric CMAC networks. Industry Applications, IEEE Transactions on. 41(1): 237-245.

Bordons C, Arce A, Del Real A, 2006. Constrained predictive control strategies for PEM fuel cells. Paper presented at the American Control Conference.

Chowdhury S, Crossley P, 2009. Micrograms and active distribution networks: The Institution of Engineering and Technology.

Dávila A, Moreno J.A, Fridman L, 2010. Variable gains super-twisting algorithm: a Lyapunov based design. sign (s). 3, 2.

Evangelista C, Puleston P, Kunusch C, 2014. Feasibility study of variable gain Super-Twisting control in fuel cells based systems. Paper presented at the Variable Structure Systems (VSS), 2014 13th International Workshop on.

Evangelista C, Puleston P, Valenciaga F, Dávila A, 2010. Variable gains super-twisting control for wind energy conversion optimization. Paper presented at the Variable Structure Systems (VSS), 2010 11th International Workshop on.

Evangelista C, Puleston P, Valenciaga F, Fridman L.M, 2013. Lyapunov-designed super-twisting sliding mode control for wind energy conversion optimization. Industrial Electronics, IEEE Transactions on. 60(2): 538-545.

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.

Gonzalez T, Moreno J. A, Fridman L, 2012. Variable gain super-twisting sliding mode control. Automatic Control, IEEE Transactions on. 57(8): 2100-2105.

Gruber J, Doll M, Bordons C, 2009. Design and experimental validation of a constrained MPC for the air feed of a fuel cell. Control Engineering Practice. 17(8): 874-885.

Gruber J. K, Bordons C, Dorado F, 2008. Nonlinear control of the air feed of a fuel cell. Paper presented at the American Control Conference.

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.

Harmouche M, Matraji I, Laghrouche S, El-Bagdouri M, 2012. Homogeneous higher order sliding mode control for PEM fuel cell. Paper presented at the Variable Structure Systems (VSS), 2012 12th International Workshop on.

Kunusch C, Puleston P. F, Mayosky M. A, Dávila A, 2010. Efficiency optimisation of an experimental PEM fuel cell system via super twisting control. Paper presented at the Variable Structure Systems (VSS), 2010 11th International Workshop on.

Kunusch C, Puleston P. F, Mayosky M. A, Fridman L, 2013. Experimental results applying second order sliding mode control to a PEM fuel cell based system. Control Engineering Practice. 21(5): 719-726.

Li Q, Chen W, Wang Y, Jia J, Han M, 2009. Nonlinear robust control of proton exchange membrane fuel cell by state feedback exact linearization. Journal of Power Sources. 194(1): 338-348.

Liu J, Laghrouche S, Wack M, 2013. Differential flatness-based observer design for a PEM fuel cell using adaptive-gain sliding mode differentiators. Paper presented at the Control Conference (ECC), 2013 European.

Matraji I, Ahmed F. S, Laghrouche S, Wack M, 2012. Extremum seeking control for net power output maximization of a PEM fuel cell using second order sliding mode. Paper presented at the Variable

Structure Systems (VSS), 2012 12th International Workshop on.
Matraji I, Laghrouche S, Wack M, 2011. Cascade control of the moto-compressor of a PEM fuel cell via second order sliding mode. Paper presented at the Decision and Control and European Control Conference (CDC-ECC), 2011 50th IEEE Conference on.
Moreno J. A, 2012. Lyapunov approach for analysis and design of second order sliding mode algorithms Sliding Modes after the first decade of the 21st Century (pp. 113-149): Springer.
Na W. K, Gou B, 2008. Feedback-linearization-based nonlinear control for PEM fuel cells. Energy Conversion, IEEE Transactions on. 23(1): 179-190.
Pukrushpan J. T, Stefanopoulou A. G, Peng H, 2004a. Control of fuel cell breathing. Control Systems, IEEE. 24(2): 30-46.
Pukrushpan J. T, Stefanopoulou A. G, Peng H, 2004b. Control of fuel cell power systems: principles, modeling, analysis and feedback design: Springer.
Slotine J-J E, Li W, 1991. Applied nonlinear control (Vol. 199): Prentice-Hall Englewood Cliffs, NJ.
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. Paper presented at the Industrial Electronics, 2009. IECON'09. 35th Annual Conference of IEEE.
Talj R, Hissel D, Ortega R, Becherif M, Hilairet M, 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. Paper presented at the Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium on.
Talj R. J, Hissel D, Ortega R, Becherif M, Hilairet M, 2010. Experimental validation of a PEM fuel-cell reduced-order model and a moto-compressor higher order sliding-mode control. Industrial Electronics, IEEE Transactions on. 57(6): 1906-1913.
Zenith F, Skogestad S, 2007. Control of fuel cell power output. Journal of process control. 17(4): 333-347.
Amir Yaghoubi Nezhad, S. H., Atefeh Mehrabi Far, Masoumeh Piryaei, Seyed Mojtaba Mostafavi. (2019). Investigation of Shigella Lipopolysaccharides Effects on Immunity Stimulation of Host Cells. International Transaction Journal of Engineering, Management, Applied Sciences and Technologies, 10, 465.
Ceisil, U. (2018). E-Awareness of University Student through Smart Phones and Developing Social Networks. Journal of Humanities Insights, 02(03), 139-145. doi:10.22034/JHI.2018.70850
Jinadu, O., Oluwafemi, S., Soyinka, M., & Akanfe, K. (2017). Effects of International Financial Reporting Standards (IFRS) on Financial Statements Comparability of Companies. Journal of Humanities Insights, 01(01), 12-16. doi:10.22034/JHI.2017.59551
Mehrabifar, A., & Rahmati, M. (2017). Investigation of Anticancer Effects of Dacarbazine Hydrogel in the Injectable Form and its Release. MedBioTech Journal, 01(01), 15-21. doi:10.22034/MBT.2017.60333
Mostafavi, S. M., Bagherzadeh, K., & Amanlou, M. (2017). A new attempt to introduce efficient inhibitors for Caspas-9 according to structure-based Pharmacophore Screening strategy and Molecular Dynamics Simulations. MedBioTech Journal, 01(01), 1-8. doi:10.22034/mbt.2017.60325
Seyed Mojtaba Mostafavi1, H. M., & Taskhiri, M. S. (2019). In Silico Prediction of Gas Chromatographic Retention Time of Some Organic Compounds on the Modified Carbon Nanotube Capillary Column. Journal of Computational and Theoretical Nanoscience, 16(151), 156.
Seyed Mojtaba Mostafavi, A. R., Mina Adibi, Farshid Pashaee, Masoumeh Piryaei. (2011). Modification of Glassy Carbon Electrode by a Simple, Inexpensive and Fast Method Using an Ionic Liquid Based on Immidazolium as Working Electrode in Electrochemical Determination of Some Biological Compounds. Asian Journal of Chemistry, 23(12).
Z. Man, A. G. E., S. M. Mostafavi,, & Surendar, A. (2019). Fuel oil characteristics and applications: economic and technological aspects. Petroleum Science and Technology.