International Journal of Innovative Computing, Information and Control
Volume **8**, Number **7(B)**, July **2012**

ICIC International ©2012 ISSN 1349-4198
pp. 5137–5148

PARAMETER ESTIMATION OF PROTON EXCHANGE MEMBRANE FUEL CELL SYSTEM USING SLIDING MODE OBSERVER

Ijaz Hussain Kazmi and Aamer Iqbal Bhatti

Department of Electronic Engineering
Mohammad Ali Jinnah University
Off Kokpul, Sehala Road, Islamabad, Pakistan
ijazkazmi2000@yahoo.com; aib@jinnah.edu.pk

Received December 2010; revised May 2011

Abstract. *Parameter estimation for health monitoring and sensorless scenario is achieved online via model-based robust state observer. The proposed dynamic algorithm observes a state (output voltage) of fuel cell system (FCS) in the presence of uncertainties and disturbances. Using this observation, membrane conductivity is estimated. The conductivity is function of water content and temperature which gives the value of water content analytically. The water content represents two important faulty modes, flooding and drying in proton exchange membrane (PEM) FCS. The water content can generally be measured through humidity sensors or other techniques. In the case of sensors, their size and cost restrict in-situ measurements whereas regarding other techniques, the extractive sampling makes measurement process slow and intrusive. Moreover, the existing measurement techniques have the issue of accuracy which is of prime importance in control and diagnostics spectra. The sliding mode technique is employed for the design of observer. The technique requires a dynamic voltage model that is developed through extensive mathematical modus operandi. The computer simulation confirms that the estimates are quite similar to nominal value. Experimental extracted range of parameter verifies the magnitude of estimated parameter and its precision is validated through offline calculation of the parameter using a model available in the literature. The observer can replace the humidity sensor which results in ridding of expensive and hard measuring instrumentation. The water content parameter estimation can provide a foundation for design of fault diagnostic schemes in PEMFCS.*

Keywords: Proton exchange membrane fuel cell system, Parameter estimation, Sliding mode observer, Humidity

1. **Introduction.** Fuel cell engine is a promising candidate for automotive propulsion due to efficient source of power along with its special characteristics like fast start-up, light weight, low operating temperature and high power density. The wide range of applications includes unmanned under water vehicle, submarines, locomotives, surface ships, buses and automobiles [1]. Despite these advantages and wide range of applications, there are still a number of challenges for the proper operation of fuel cell system. Water management is one of them. This issue is dealt with different approaches that may include designing membrane electrode assembly, hardware and system design and controlling of stack operating conditions. The former approach rests with manufacture's part and may include cell orientation at an acute angle towards air outlet port and cell shaking during fuel cell operation whereas latter is concerned with fuel cell system operation and may include maintaining of operating temperature, pressure, stoichiometry and the humidification levels of reactant gases. Water management consists of three stages namely water treatment, humidification of reactant gases and water removal process. However,

all these remedies are feasible at that time when water content level is known in the stack and can be monitored efficiently.

Water content measurement is very important in the condition monitoring of fuel cells. The precise and exact estimation of water content plays a pivotal role in its management for the sustenance of chemical reactions. The water content can generally be measured through humidity sensors or other techniques. In the case of sensors, their size and cost restrict in-situ measurements whereas regarding other techniques, the extractive sampling makes measurement process slow and intrusive. Moreover, the existing measurement techniques have the issue of accuracy which is of prime importance in control and diagnostics spectra. In the conventional measurement method, the humidity sensors are used which are prohibitive for in-situ measurement due to their size and cost. Their accuracy is also not always satisfactory for high relative humidity levels. However, the gas chromatography technique is relatively accurate but it needs extractive sampling which makes it slow and intrusive. Other techniques such as neutron radiography and real-time gas analyzer have their own issues. The optical devices which access the water fronts and distribution in transparent cell plates are used for direct visualization. The optical devices may include digital camcorders, high-speed cameras, infrared cameras and Charge-Coupled Device cameras. Nuclear Magnetic Resonance imaging or Magnetic Resonance Imaging, is used for measuring water distribution of an operating fuel cell in situ. Beam interrogation approaches include neutron imaging, electron microscopy, X-rays techniques. Fluorescence microscopy provides the micro scale transport of liquid water [2]. All these techniques can be employed for off-line analysis and diagnostics. For the controlling of operating parameters, online estimation is required for control and diagnostics purposes. There are numerous works reported in the literature therein water management has been given vital importance for good performance of the system developing mathematical models, analyzing process and devising detection techniques.

Various schemes were devised to detect and predict the water content level in the stack in recent years. Thawarnkuno and Panjapornpon [3] proposed a technique to predict the water content using state estimation. They estimated the water content via extended Luenberger observer. This technique demonstrated better results than open loop observer. McKay and Stenfanopoulou [4] developed and then validated mathematical model for membrane humidity in the stack. They used open loop observer to estimate the humidity. Gorgun et al. [5,6] proposed an algorithm for the estimation of water content in PEM fuel cell exploiting its effects on cell resistance voltage drop. The algorithm requires measurements of voltage, current, temperature and total pressure values in the cathode and anode. Using these measurements they calculated the membrane resistance and then analytically obtained an estimate of water content. The scheme cannot be applied for zero or small value of current whereas anode flooding occurs at low current densities. Another problem with this scheme is that a number of estimators are required for observation of partial pressures of hydrogen and oxygen, etc. In this paper, a model-based sliding mode observer has been designed and tested with simulations. First order sliding mode observer estimates the parameter with fast convergence to its nominal value. The proposed algorithm employs a dynamic voltage mathematical model and estimates water content parameter online. The scheme is equally applicable in the scenario of low value of current and even in no load conditions. The algorithm has feedback characteristics; therefore, it delivers better results than open loop observers. The observer is based on sliding mode technique. The observer estimates output voltage of the system. Using this observation, membrane conductivity is estimated. The conductivity is function of water content and temperature. Then water content is calculated analytically. The sliding mode technique is used first time so far.

The paper is organized as follows. Section 2 contains fuel cell system description with its physical parameters. The water dynamics across the membrane are explained. Section 3 presents the observer design. It includes a dynamical voltage model and sliding mode observer theory. The error dynamics and stability analysis are also presented. In Section 4, simulation studies are presented in detail to validate the scheme. Finally, concluding remarks are given in Section 5.

2. **Fuel Cell System.** The fuel cell system consists of fuel cell stack and auxiliary subsystems. A schematic diagram of the fuel cell system is shown in Figure 1.

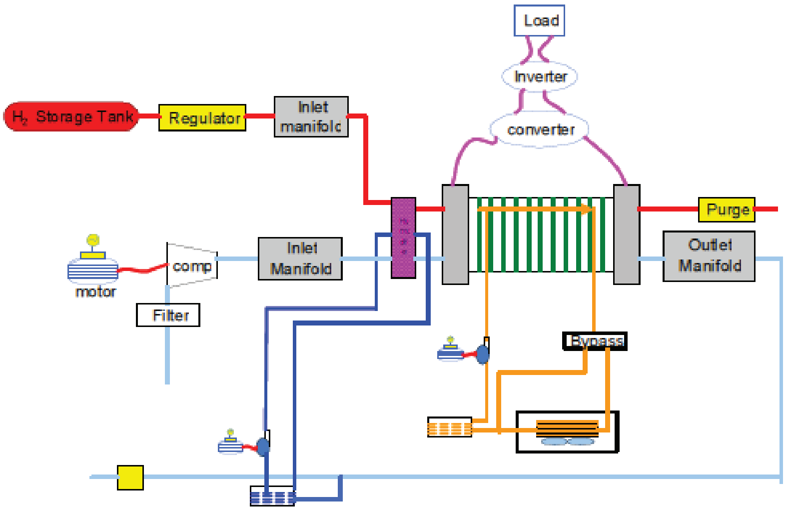

FIGURE 1. Schematic diagram of fuel cell system

The core of the system is the fuel cell stack. Its components are membranes, catalysts, gas diffusion layers, bipolar and end plates. The auxiliary systems are the air supply system, the fuel supply system, the humidification system, the cooling system and the power conditioning system. The air supply system comprises electric motor, air compressor and manifolds whereas fuel supply system has fuel storage cylinder. The humidification system consists of pump and valves, etc. The coolant system contains a radiator, a pump, a manifold, valves and a reservoir. The power conditioning system contains the converter and inverter. The parameters of fuel cell stack are given in Table 1. Most of these parameters are derived from a prototype fuel cell vehicle. Other parameters are either calculated from the peak power of the stack or approximated from the dimensions of the prototype by [7].

TABLE 1. Parameters of fuel cell stack

Symbol	Description	Value
δ_m	membrane width	0.0001275 m
n	number of cells in stack	381
A_{fc}	fuel cell active area	0.028 m^2
V_{an}	anode volume	0.005 m^3
V_{sm}	supply manifold volume	0.02 m^3
V_{rm}	return manifold volume	0.005 m^3
P	power	75 kW

The water dynamics consists of electro-osmotic drag from anode to cathode and back diffusion from cathode to anode across the membrane as shown in Figure 2. During operation of the system, the water is produced at the cathode. The presence of water contents in the stack is sensitive to cold environment, reactant gases transportation, proton conductivity and length of membrane life. In the cold environment, the water content can change its phase in the stack due to subfreezing temperature. In this scenario, the water content can increase start-up time of the system.

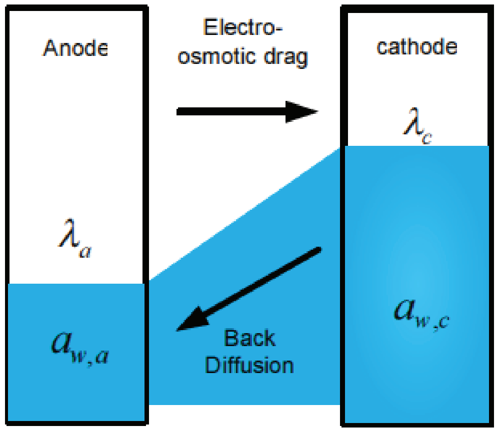

FIGURE 2. Schematic diagram of water dynamics in a fuel cell system

Insufficient and excessive amount of water content in the stack affects negatively the performance of fuel cell system. The inadequate amount of water can cause the membrane dryness and then would create cracks in the membrane. The dry membrane has higher internal resistance which increases the voltage losses. The cracks in the membrane degrade the performance and shorten the stack life. On the other side, the excessive water content causes flooding in the stack and fills the pores of the porous gas diffusion layer and prevents the distribution of the reactants to the catalyst. The situation becomes severe at high current densities. This state occurs not only at cathode side but the anode also gets affected. The produced water at the cathode diffuses into the anode side due to the gradient of water concentration. The anode having close end at outlet side is severe victim of the process because water accumulates there and hinders the adequate distribution of fuel gas. If water content level is known in the stack and can be monitored efficiently then remedial action can be proposed. An observer can be good choice for estimation of water content. In the literature, model-based observation techniques are available and being employed for a variety of industrial systems.

3. **Model Based Observer Design.** Model-based observers are often used for the estimation of model parameters in industrial engineering processes [8-11]. These observers are also used for control, diagnostics and communication [12,13] respectively. Different model-based techniques have been employed for the estimation of states and parameters, e.g., Kalman filters, Luenberger observers and sliding modes [8-10]. Kalman observers need linearized models whereas Luenberger observers usually require models of high accuracy and are sensitive to uncertainties and modeling errors. Sliding mode technique dose not need linear model and is robust to modeling errors and uncertainties. Sliding mode observers (SMOs) are also simple in structure; therefore, the technique can be implemented easily that is why this technique is highly valued among the research community. It has been applied in a variety of industrial applications in recent years but so far no

SMO has been used for water content estimation. Kim and his coworkers designed nonlinear observer for the estimation of PEM fuel cell system in which different pressures were estimated via SMO [10]. The SMO applied for estimation of mass flow rate of PEM fuel cell system with an unknown input, i.e., load current [14].

3.1. **Model development.** In order to design the observer, a dynamical voltage model is developed through rigorous mathematical procedure. In the development of dynamic model, a nonlinear algebraic voltage model [7] was considered. The dynamic model is as follows:

$$\dot{V}_{fc} = \varphi \dot{x}_3 + \phi \dot{x}_4 + \chi \dot{x}_8 + \psi \frac{di}{dt} + t_m \frac{di}{dt} \tilde{\sigma}_m \tag{1}$$

where $\tilde{\sigma}_m = \frac{1}{\sigma_m}$ and σ_m is the conductivity of membrane against hydrogen ions. The coefficient functions φ, ϕ, χ and ψ are detailed as follows:

$$\varphi = d_6 \frac{T_{fc}}{p_{ca} - p_{sat}} \tag{2}$$

$$\begin{aligned} \phi = {} & e_3 \frac{T_{fc}}{p_{O_2}} + C_1 T_{fc} p_{O_2} + C_3 T_{fc} p_{sat} - C_5 - C_6 p_{sat} \\ & - C_7 T_{fc} + \frac{1}{i_{\max}{}^{C_3}} i^{C_3+1} C_3 C_2{}^{C_3} (m_5 T_{fc} - m_5) \end{aligned} \tag{3}$$

$$\chi = e_3 \frac{T_{fc}}{p_{H_2}} \tag{4}$$

$$\psi = -C_1 V_a \exp - C_1 i - \frac{1}{i_{\max}{}^{C_3}} C_2{}^{C_3} (C_3 + 1) i^{C_3} \tag{5}$$

The conductivity parameter is to be estimated; therefore, a slight uncertainty is introduced as under. We get a perturbed voltage model as follows:

$$\dot{V}_{fc} = \varphi \dot{x}_3 + \phi \dot{x}_4 + \chi \dot{x}_8 + \psi \frac{di}{dt} + t_m \frac{di}{dt} \left(\tilde{\sigma}_m + \Delta \tilde{\sigma}_m \right) \tag{6}$$

The ultimate task of this work is to calculate the water content parameter λ_m. As the perturbation on conductivity is recovered then the conductivity is updated by correction term $\Delta\tilde{\sigma}_m$. The λ_m can be calculated by following model [15].

$$\lambda_m = \frac{1}{\Delta \tilde{\sigma}_m b_{11} \exp\left(b_2 \left(\frac{1}{303} - \frac{1}{T_{fc}} \right) \right)} + \frac{b_{12}}{b_{11}} \tag{7}$$

where $\Delta\tilde{\sigma}_m$ is correction term, b_{11} and b_{12} are related to the Nafion membrane [15] and b_2 is a fitting parameter [7].

3.2. **Sliding mode observer.** A sliding mode observer (SMO) is an observer which exploits sliding mode control concepts for devise of an arrangement to minimize its error [16]. The sliding mode technique does not need a linear model for observer design because of its inherent nonlinear characteristics and it holds for nonlinear systems [17-20]. The technique is robust to modeling errors and uncertainties. The SMO is also simple in structure; therefore, it can easily be implemented. It is designed through two steps: in the first step, a sliding surface is created whose zero value confirms accomplishment of the task of observer. In the second step, a discontinuous nonlinear term is injected which ensures the sliding modes [16]. That is why this technique is highly valued among research community. It has been applied in a variety of industrial applications in recent years [14,21,22]. In this work, an SMO is designed on perturbed voltage model assuming that the measurements of inlet manifold pressure, partial pressures of oxygen and hydrogen are known. The observer of inlet manifold pressure is a previous work of the authors [14]. The partial pressures of reactant gases are assumed to be known. The proposed structure of the observer for sliding mode observation of output voltage of PEM fuel cell system is designed on perturbed model as follows:

$$\dot{\hat{V}}_{fc} = \varphi\dot{x}_3 + \phi\dot{x}_4 + \chi\dot{x}_8 + \psi\frac{di}{dt} + t_m\frac{di}{dt}\tilde{\sigma}_m + \nu \tag{8}$$

where ν is the injector term of the observer. The injector compensates the perturbations or uncertainties in V_{fc} and is a product of switching function and a design constant. The constant is designed so that the observer remains in the sliding mode despite perturbations and uncertainties. It can be expressed as:

$$\nu = Ksign\left(V_{fc} - \hat{V}_{fc}\right) \tag{9}$$

where K is positive sliding mode design constant and has a lower bound. The bound is derived through the stability analysis of the observer. The $sign(.)$ is the nonlinear switching function which can be expressed mathematically as follows:

$$sign(.) = \begin{cases} +1 & \text{if } sign(.) > 0 \\ -1 & \text{otherwise} \end{cases} \tag{10}$$

3.3. **Error dynamics.** The observer error is defined as the difference between, the fuel cell voltage and observed fuel cell voltage as follows:

$$e = V_{fc} - \hat{V}_{fc} \tag{11}$$

The observer has a task to steer its error to zero. The equation for observer error dynamics is obtained by subtracting Equation (8) from Equation (6) as follows:

$$\dot{e} = -\Delta\tilde{\sigma}_m t_m\frac{di}{dt} - Ksign(e) \tag{12}$$

If the observer steers its error to zero then the following relationship can be obtained from Equation (12) for $e = 0$ and $\dot{e} = 0$

$$\Delta\tilde{\sigma}_m = \frac{-Ksign(e)}{t_m\frac{di}{dt}} \tag{13}$$

which is employed to recover the perturbation in the conductivity of fuel cells across the membrane.

3.4. **Stability analysis.** The stability analysis of the observer is investigated by taking the proposed Lyapaunov candidate function (V) of quadratic form as follows:

$$V = \frac{1}{2}e^2 \tag{14}$$

The globally asymptotically stability can be ensured provided that the Lyapunov conditions are realized. The candidate function should be positive. Its derivative is strict negative definite. Moreover, the function is divergent at infinity. It is obvious that the function is positive definite due to its quadratic characteristics. Secondly, its derivative must be negative definite which will ensure its asymptotic decay and convergence. Taking its derivative as follows:

$$\dot{V} = -\Delta\tilde{\sigma}_m t_m\frac{di}{dt} - e\nu \tag{15}$$

The right hand side of above equation can be investigated for strict negative definiteness. Negative definiteness demands the existence of the following constraint giving the lower bound of the switching gain of the observer.

$$K > \left| \Delta\tilde{\sigma}_m t_m \frac{di}{dt} \right| \tag{16}$$

The switching gain is governed by thickness of membrane and conductivity. Both are finite values but current derivative cannot be determined. The technique has an unknown input characteristic. The load current is unknown to observer. Therefore, change in load current will not define the magnitude of the gain. The value of switching gain within the bounds will guarantee the stability.

4. **Results and Discussion.** In this section, the results of simulation are presented by using the figures. The parameters for simulation are based on fuel cell prototype vehicle [7]. The observer is tested with simulations in configuration as shown in Figure 3. The load current input is unknown to the observer. The error is generated via comparing the measured and observed state, i.e., output voltage. The value of water content parameter

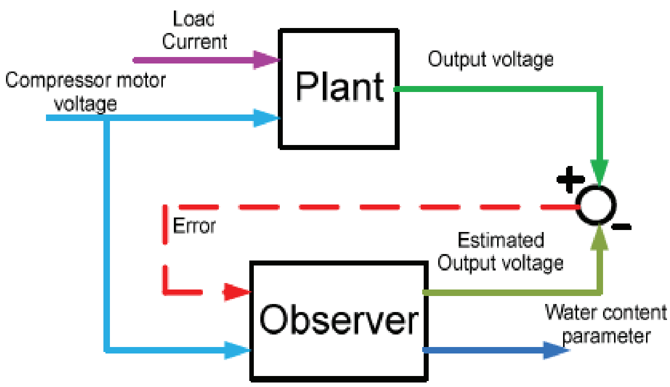

Figure 3. Schematic diagram of plant-observer configuration

is estimated online using the proposed observer. The estimated value of parameter lies in the range of 0 to 14. Moreover, the parameter is calculated offline from the model available in the literature [15]. In this way, it is tried to verify the results of estimation of parameter.

4.1. **Simulations.** The observer design is tested on simulations for tracking, robustness and chattering phenomena. The simulations are run with constant load, i.e., 100 Amperes current and compressor motor voltage is varied from 100 to 250 volts as shown in Figure 4. This input is known to the observer but second input that is load current is not known to the observer. Therefore, the observer can be considered as partial known input observer (PKIO). This load current acts as input to the observer which has a profile of similar to impulse. The load current and its differentiated profiles are shown in Figure 5.

The performance of the proposed observer is shown in Figure 6. The observer tracks the measured voltage with robustness. The inherent chattering phenomenon of standard sliding mode observer is obvious from the results. The chattering effect can be mitigated using higher sliding mode observer or other methods given in the literature. The conductivity across the membrane of fuel cell is shown in Figure 7. The degree of results is reasonable and acceptable. There are over shoots because of derivative of load current as

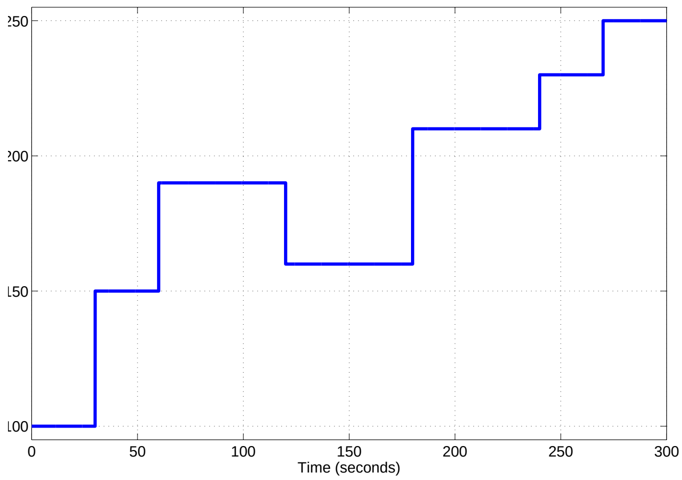

FIGURE 4. Profile of compressor motor voltage

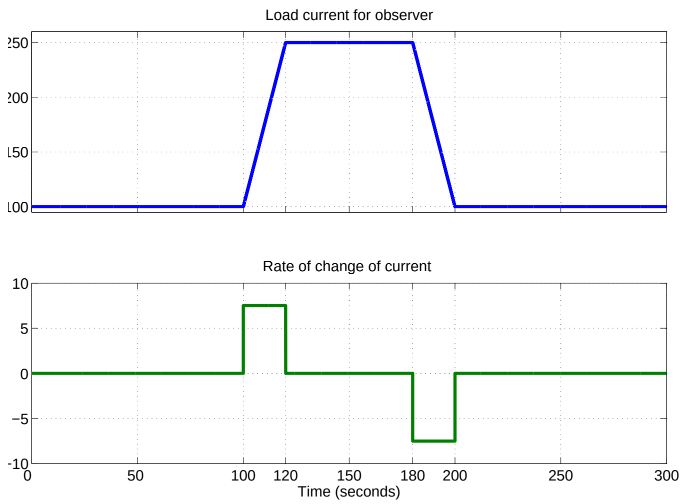

FIGURE 5. Load current and its differentiated behavior

load changes, the shoots are experienced. By using a low pass filter, the results are made understandable.

The estimated value of conductivity is employed for the calculation of water contents parameter using the procedure narrated in the previous section. The maximum value of water content parameter shows that the humidity is 96 per cent approximately. The water content parameter is shown in Figure 8.

In the load current profile from 100 seconds to 120 seconds and from 180 seconds to 200 seconds, there are increasing slope and decreasing slop respectively as shown in Figure 5. The change in load current affects the water current parameter. The change in load current affects the water content parameter. As the load current increases, there is dryness process across the membrane. When the load current decreases the wetting process occurs. In practical the dryness process is slow and wetting process is fast. These dynamics can be viewed in Figure 9. It contains zoomed view of Figure 8 from 80 seconds to 220 seconds.

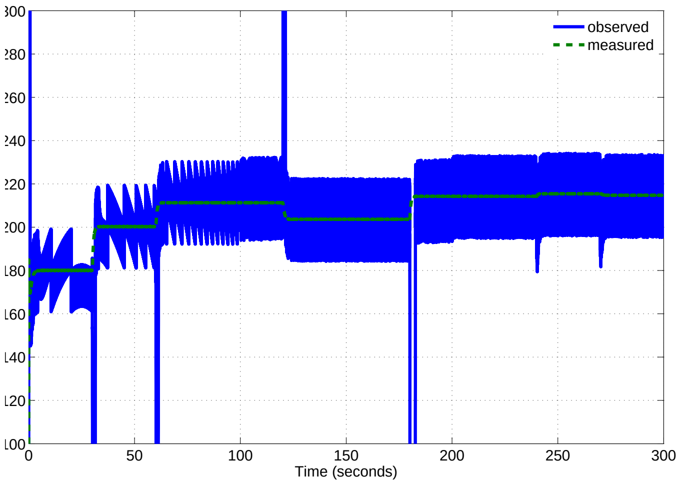

FIGURE 6. Output voltages of system and observer

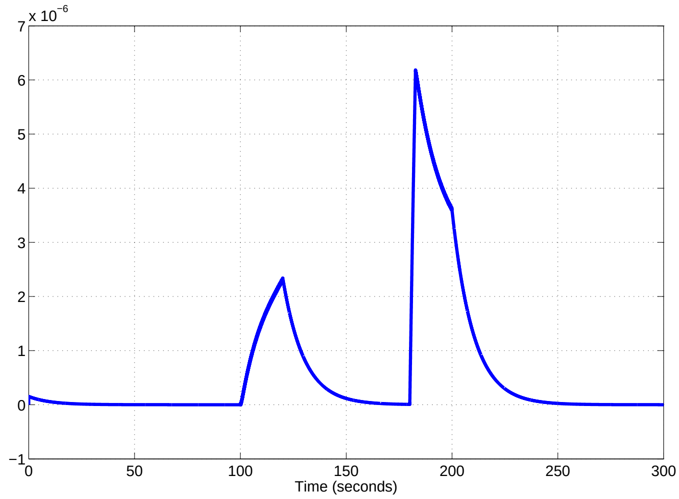

FIGURE 7. Conductivity across the membrane of fuel cell

4.2. **Verification.** The verification of estimates is offline process whereas the parameter estimation via proposed observer is online process. Using ideal gas law, the vapor pressure at cathode is calculated as

$$p_{v,\ ca} = \frac{R_v T_{st}}{V_{ca}} m_{v,\ ca,\ \max} \tag{17}$$

where the value of maximum mass of vapors at cathode side was used as 0.0028 kg [23]. The water activity was found using the vapor pressure and saturated vapor pressure at stack temperature as follows:

$$a_{ca} = \frac{p_{v,\ ca}}{p_{sat}(T_{st})} \tag{18}$$

Finally, a third order polynomial [15] was used to calculate the value of water content parameter. The model is quit reliable and consistently employed for calculation of the

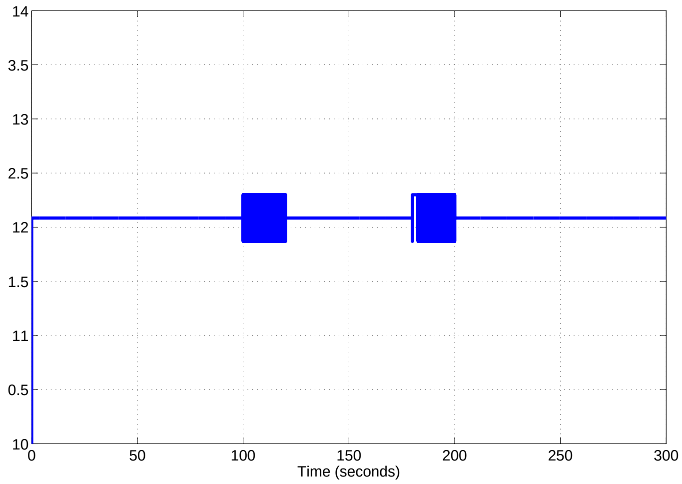

FIGURE 8. Water contents across the membrane of fuel cell

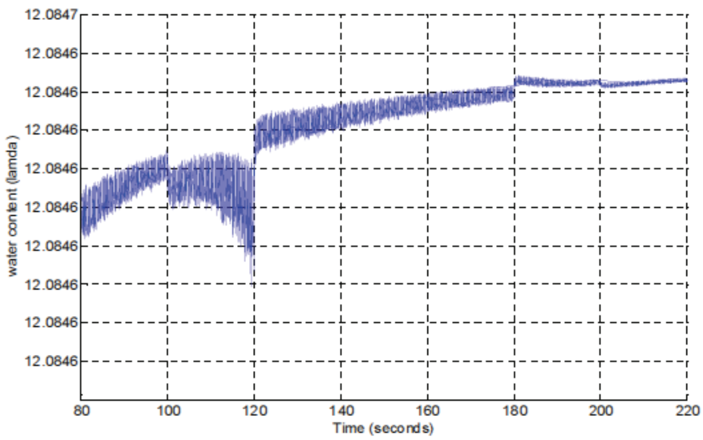

FIGURE 9. Water contents behaviors under load transients

parameter as it is reported in literature recently [24].

$$\lambda_m = \begin{cases} 0.043 + 17.8a_{ca} - 39.85a_{ca}^2 + 36a_{ca}^3 & 0 < a_{ca} \leq 1 \\ 14 + 1.4(a_{ca} - 1) & 1 < a_{ca} \leq 3 \end{cases} \tag{19}$$

where water activity a_{ca} was found less than unity; therefore, first part of Equation (19) was used to obtain the value of water content parameter. The difference is less than 5 percent and therefore simulation results are quite reasonable and compatible. The comparison of online and offline results is shown in Table 2.

TABLE 2. Comparison of water content parameter

Description	Online estimation	Offline calculation	Difference
value	12.0845	12.6501	0.5656

5. **Conclusions.** Water content parameter estimation based on sliding mode observer was presented in the paper. The accuracy of observer was established via comparison

between outputs of observer and nonlinear dynamical model. The effects of load current and static humidification were obvious in the results. The two faulty modes, drying and flooding due to load transients across the membrane were discussed. Validated water content parameter estimation can be used in fault diagnosis and prognosis in PEM fuel cell system. The observer design is based on first order sliding mode technique. The observer structure is simple; hence, it is easy to implement. The estimates are quite closer to nominal values with chattering phenomenon. The chattering mitigation in observer results will be future work.

Acknowledgment. The authors appreciatively acknowledge the financial support provided by Higher Education Commission (HEC), Pakistan for execution the research. The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

REFERENCES

[1] Y. Wang, K. S. Chen, J. Mishler, S. C. Cho and X. C. Adroher, A review of polymer electrolyte membrane fuel cells technology, applications, and needs on fundamental research, *Applied Energy*, vol.88, pp.981-1007, 2011.

[2] M. Ji and Z. Wei, A review of water management in polymer electrolyte membrane fuel cells, *Energies*, vol.2, pp.1057-1106, 2009.

[3] C. Thawornkuno and C. Panjapornpon, Estimation of water content in PEM fuel cell, *Chiang Mai J. of Science*, vol.35, no.1, pp.212-220, 2008.

[4] D. McKay and A. G. Stefanopoulou, Parameterization and validation of a lumped parameter diffusion model for fuel cell stack membrane humidity estimation, *IEEE Proc. of 2004 American Control Conference*, pp.816-821, 2004.

[5] H. Gorgun, M. Arcak and F. Barbir, A voltage-based observer design for membrane water content in PEM fuel cells, *American Control Conference*, USA, 2005.

[6] H. Gorgun, M. Arcak and F. Barbir, An algorithm for estimation of membrane water content in PEM fuel cells, *J. of Power Sources*, vol.157, pp.389-394, 2006.

[7] J. T. Pukrushpan, H. Peng and A. G. Stefanopoulou, Control-oriented modeling and analysis for automotive fuel cell systems, *ASME J. of Dynamic Systems, Measurement and Control*, vol.126, no.1, pp.14-25, 2004.

[8] S. Ibrir and D. Cheddie, Model-based estimation of PEM fuel-cell systems, *IEEE MSC, Saint Petersburg*, Russia, 2009.

[9] R. Kandepu, B. Huang, L. Imsland and B. Foss, Comparative study of state estimation of fuel cell hybrid system using UKF and EKF, *IEEE Int. Conf. on Control and Automation*, Guangzhou, China, 2007.

[10] E. S. Kim, C. J. Kim and K. S. Eom, Nonlinear observer design for PEM fuel cell systems, *Proc. of Int. Conf. on Electrical Machines and Systems*, Seoul, Korea, 2007.

[11] M. Arcak, H. Gorgun, L. M. Pedersen and S. Varigonda, A nonlinear observer design for fuel cell hydrogen estimation, *IEEE Trans. of Control Systems Technology*, vol.12, no.1, 2004.

[12] A. Forrai, H. Funato, Y. Yanagita and Y. Kato, Fuel-cell parameter estimation and diagnostics, *IEEE Trans. on Energy Conversion*, vol.20, no.3, 2005.

[13] M. Boutayeb, M. Darouach and H. Rafaralahy, Generalized state-space observers for chaotic synchronization and secure communication, *IEEE Trans. Circuits Syst. I*, vol.49, no.3, pp.345-349, 2002.

[14] I. H. Kazmi, A. I. Bhatti and M. Iqbal, Parameter estimation of PEMFC system with unknown input, *Int. Workshop on Variable Structure Systems*, Mexico, 2010.

[15] T. E. Springer, T. A. Zawodzinski and S. Gottesfeld, Polymer electrolyte fuel cell model, *J. Electrochem. Soc.*, vol.138, no.8, pp.2334-2342, 1991.

[16] V. I. Utkin, *Sliding Modes in Control and Optimization*, Springer, 1992.

[17] H. Xing, D. Li and X. Zhong, Sliding mode control for a class of parabolic uncertain distributed parameter systems with time-varying delays, *International Journal of Innovative Computing, Information and Control*, vol.5, no.9, pp.2689-2702, 2009.

[18] X. Liu and W. Wang, High order sliding mode and its application on the tracking control of piezoelectric systems, *International Journal of Innovative Computing, Information and Control*, vol.4, no.3, pp.697-704, 2008.

[19] W. Xiang and F. Chen, Sliding mode control strategies for the hyperchaotic MCK system, *ICIC Express Letters*, vol.3, no.3(A), pp.283-288, 2009.

[20] C. Xia, X. Wang, S. Li and X. Chen, Integral sliding mode control of PMSM speed-regulation system, *ICIC Express Letters*, vol.3, no.4(A), pp.1049-1054, 2009.

[21] Q. R. Butt and A. I. Bhatti, Estimation of gasoline engine parameters using higher order sliding mode, *IEEE Transactions on Industrial Electronics*, vol.55, no.11, 2008.

[22] S. Iqbal, C. Edwards and A. I. Bhatti, Robust output feedback linearization for minimum phase systems, *The 18th IFAC World Congress*, Milano, Italy, 2011.

[23] C. Kunusch, P. F. Puleston, M. A. Mayosky and J. Riera, Sliding mode strategy for PEM fuel cells stacks breathing control using a super-twisting algorithm, *IEEE Trans. on Control Systems Technology*, vol.17, no.1, 2009.

[24] F. Gao, B. Blunier, A. Miraoui and A. El Moudni, A multiphysic dynamic 1-D model of a proton-exchange-membrane fuel-cell stack for real-time simulation, *IEEE Transactions on Industrial Electronics*, vol.57, no.6, 2010.