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Robust Combined Control of Proton Exchange Membrane Fuel Cell Equipped by Boost Converter

Hassan Khosh Kholgh Sima[1], Alireza Sahab[1*], Abdul Reza Tavakoli[1], Hussein Mahdinia Roudsari[1]

[1] Department of Electrical Engineering, Lahijan Branch, Islamic Azad University, Lahijan, Iran.

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Abstract

The fuel cell, especially its PEM type, is one of the most important sources of renewable energy, and considering the importance of energy in today's life, this paper presents a new solution to increase and optimize the output power of the PEM fuel cell. To extract the maximum power, the structure of PEM fuel cell equipped with boost converter is considered and this study presents the following innovations in this regard. To overcome the non-minimum phase and destabilizing nature of the boost converter, a hybrid robust control scheme is designed for the boost converter located at the output of the fuel cell stack. Two reset and adaptive sliding mode techniques in an innovative and hybrid design form the foundations of the planned scheme. Despite its simplicity, the reset technique has a high ability to eliminate the steady-state error, improve the transient and permanent dynamic response, and of course overcome the limitations of linear controllers. The planned sliding mode control technique is also an adaptive super twisting type, which is used to ensure the robustness and reliable performance of the controller against uncertainties and disturbances. The planned control scheme increases the power extracted from the PEM fuel cell by improving the performance of the boost converter and provides more efficiency than other techniques by stabilizing the output voltage from the PEM fuel cell and stack as well as ensuring stability. The outcomes of the implementation in the MATLAB environment and evaluation with the PI adaptive sliding mode method guarantee the efficiency and capability of the scheduled robust design.

Keywords: PEM Fuel Cell; Boost Converter; Reset Robust Control; Adaptive Super Twisting Sliding Mode Control; Uncertainty; Lyapunov; Output Power; Renewable Energy.

1. INTRODUCTION

In recent years, the development and use of renewable energy have grown significantly

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*****Corresponding Authors Email: sahab.alirezza@gmail.com

and increasingly [1]. The main reasons for this are the natural periodicity of renewable energy sources, the rapid reduction of fossil energy sources, and the challenge of the ever-increasing world energy demand [2]. One of the most important sources of renewable energy, which is also the goal of this study, is the hydrogen fuel cell [3]. Hydrogen energy and fuel cells are the most promising green and clean alternative energy sources and energy conversion devices in the future because they produce little or no carbon emissions and pollution, depending on whether the hydrogen is produced from non-renewable or renewable primary energy sources and they are more efficient than other alternative and renewable energy sources and energy conversion technology [4-7].

Among fuel cells, proton exchange membrane fuel cells (PEMFCs) have many advantages over other types of fuel cells, including short start-up time, high power density, and relatively low operating temperature [8-9]. Therefore, they are seen as possible contenders for various applications, such as stationary power generation, portable energy sources, and electric vehicles, where clean and efficient energy conversion is crucial [10-11].

Due to several operational and environmental advantages, PEMFCs are very important in the field of clean energy and sustainable transportation [12-14]. PEMFCs are zero-emission energy sources, producing no nitrogen oxides, sulfur oxides, or carbon dioxide, and generate electricity through an electrochemical reaction that only results in the byproduct of water. This is in direct contrast to traditional combustion engines that emit greenhouse gases and air pollutants that contribute to climate change and poor air quality. High energy conversion efficiency is the next advantage of PEMFC cells compared to internal combustion engines, and this feature leads to less energy loss and better use of fuel and helps their sustainability. Also, the hydrogen used as fuel in PEMFCs can be produced from renewable sources such as solar energy, wind, and hydroelectricity through water electrolysis. This makes hydrogen a

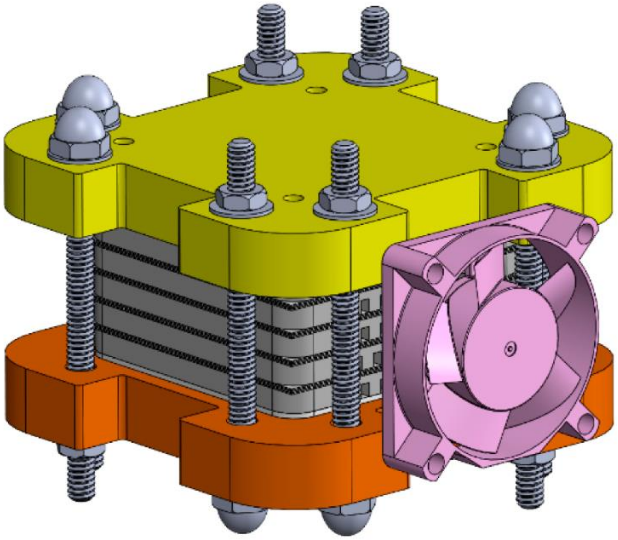

Fig. 1. A schematic of a PEMFC stack configuration.

sustainable and renewable energy carrier that can be used in PEMFCs to generate clean electricity [15]. The use of PEMFCs in electric vehicles (EVs) can also help decarbonize the transportation sector, which is one of the main sources of greenhouse gas emissions. PEMFCs, especially when combined with renewable energy sources, can contribute to grid sustainability and more resilient energy infrastructure by providing distributed power generation and acting as an energy storage tool.

An electrochemical energy conversion device PEMFC uses the chemical reaction between hydrogen and oxygen to generate electricity and consists of the main parts of an anode, a cathode, and a proton exchange membrane. Fuel cells were first developed as single cells and later adapted to a stacked configuration to adjust their power output according to the load to which they are connected. A schematic of a PEMFC stack configuration is shown in Figure 1.

Performance, cost, and durability are the three main issues that PEMFC technology must overcome in order to be widely and successfully used in various applications. In terms of performance, elements such as the conductivity of the proton exchange membrane, the strength of the electrochemical reaction catalysts, and the mass movement within the fuel cell all affect the efficiency and power density of PEMFCs. Improvement in these areas is necessary to achieve acceptable performance [16-20].

Of course, the mentioned cases include most of the structural areas and changes in the construction and configuration of the PEM fuel cell, but post-construction theoretical methods should also be considered more in this field. PEM fuel cell structures equipped with power electronic devices are one of the special works done in this field and useful and relatively comprehensive studies have been done in this regard [21-23]. In line with the previous works, this article pursues the most important goal of the PEM fuel cell, that is, extracting the maximum possible power by performing control actions and designing a robust controller on the boost converter located at the output of the PEM fuel cell stack. The structure under study has the ability to give a suitable output power with an almost stabilized voltage level, and the present study follows the approach of extracting the maximum power by relying on post-fabrication theoretical methods, in order to improve the performance of the fuel cell stack by presenting a novel hybrid robust control method.

One of the most common structures to convert the output power of the fuel cell into a suitable power for various applications is the use of DC/DC converters. There are different topologies in the use of converters, the most popular of which are buck converters (voltage reducers), boost converters that increase voltage, and other types of buck-boost converters, etc. [24]. In order to achieve more power conversion efficiency from the fuel cell stack, many control techniques have been used to operate the system at the maximum power point. Due to non-linearity, uncertainty, and disturbances, classical linear control methods are not effective for DC/DC converters and recently, special attention has been paid to advanced methods such as artificial neural network (ANN) [25], particle swarm optimization (PSO) [26], feedback linearization [27], fuzzy logic controller (FLC) [28-29], and sliding mode controller (SMC) [30-33]. The sliding mode controller has been used in various fields due to several advantages, including the ability to stabilize the system against changes in the converter parameters and load disturbances [34-36], ease of implementation, and excellent performance [37-38].

But using the sliding mode controller alone in the DC-DC converter causes several major problems which are the excitation of low harmonics, the creation of steady-state error, the instability of the closed loop system due to the inability of the controller regarding the zero on the right side in the transfer function of the converter, and the appearance of noise effects. Therefore, it is necessary to adopt corrective approaches in relation to the controller. On the other hand, we know that the microbial fuel cell is mostly affected by changes in environmental conditions, there is parameter uncertainty both in the converter and the fuel cell model due to ignoring some dynamic and static equations, and of course, load changes and disturbances can also be added to these undesirable elements in the way of optimal control and extracting the maximum power from the PEM fuel cell stack.

Considering the above points, this paper presents a new robust hybrid approach to control the PEM fuel cell stack with a boost converter. The reset method, which is one of the simplest robust approaches to remove permanent error and improve the transient and permanent response, is used together with the sliding mode method, and a robust joint scheme is designed that is able to overcome the effects of uncertainty, disturbance, environmental changes, and also load changes in the output of the fuel cell and converter. The planned adaptive method is able to estimate uncertainties with an unknown upper limit and in addition, the built-in robust technique is able to overcome the zero effects of the right-hand side of the converter transform function and provides a stabilized output voltage along with maximum extractable power from the PEM fuel cell stack.

Accordingly, the structure of this article is as follows: The second part describes the PEM fuel cell model with DC-DC converter and the third part presents the structure of the proposed hybrid robust control approach. In the fourth part, the results of simulation and comparison in the MATLAB environment are given. Finally, the fifth section is devoted to conclusions and future suggestions.

2. MODEL OF PEM FUEL CELL STACK WITH BOOST CONVERTER

This section describes the dynamic model of the PEM fuel cell system equipped with a boost converter. The main function of the PEM fuel cell is to convert chemical energy into electrical energy through several chemical reactions of oxidation, reduction, and combination in different parts of the cell. The schematic of the main parts of the PEM fuel cell is shown in Figure 2, which includes the anode, cathode, and membrane.

During the process of chemical reactions inside the fuel cell, in addition to electrical energy, a large amount of water is also produced, and of course, the output voltage of the single and stack fuel cell is obtained from the following relations.

$$V_{Fc} = E_{Cell} - \eta_{act} - \eta_{ohm} - \eta_{con} \qquad (1)$$

$$V_{stack} = N_{cell}.V_{Fc} = N_{cell}.(E_{cell} - \eta_{act} - \eta_{ohm} - \eta_{con}) \qquad (2)$$

In the relations (1) and (2), E_{Cell} indicates the electrochemical thermodynamics potential of the PEMFC and it reports the best amount of voltage, η_{act} specifies activation polarization loss and states the voltage drop due to the activation of the anode and the cathode, η_{ohm} shows ohmic polarization loss caused by the resistance of the membrane for the movement of protons and the electrical resistance of the electrodes for the movement of electrons, η_{con} indicates concentration polarization loss caused by a decrease in the concentration of reactants, oxygen and hydrogen, and changes through the reaction and N_{cell} shows the number of fuel cell in stack.

Considering the similar behavior of the capacitor for the membrane due to being located between two charged layers in the PEM cell, paying attention to the Kirchhoff's circuit laws and of course the reference [39], the output voltage of the fuel cell is in the form of the following equation:

$$V_{cell} = E_{cell} - \left(\frac{R_{act}+R_{con}}{(R_{act}+R_{con})C.s+1} + R_{ohm}\right) I \qquad (3)$$

In the above equation, R_{ohm}, R_{act}, and R_{con} are ohmic, activation, and concentration resistances, respectively, and C is the equivalent capacitor. Now, by considering the partial equations for oxygen and hydrogen in equations 4 and 5, a more detailed description of PEMFC behavior can be provided, as shown in Figure 3.

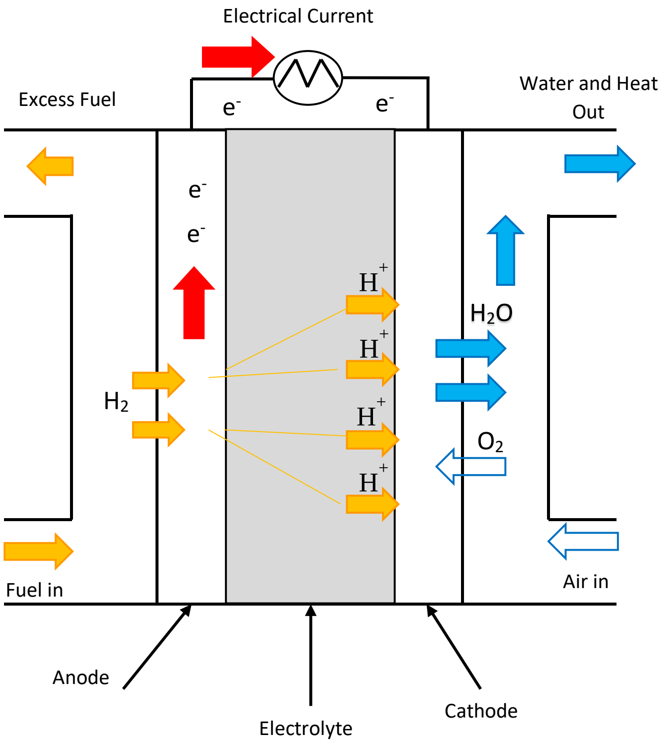

Fig. 2. Different parts of PEM fuel cell.

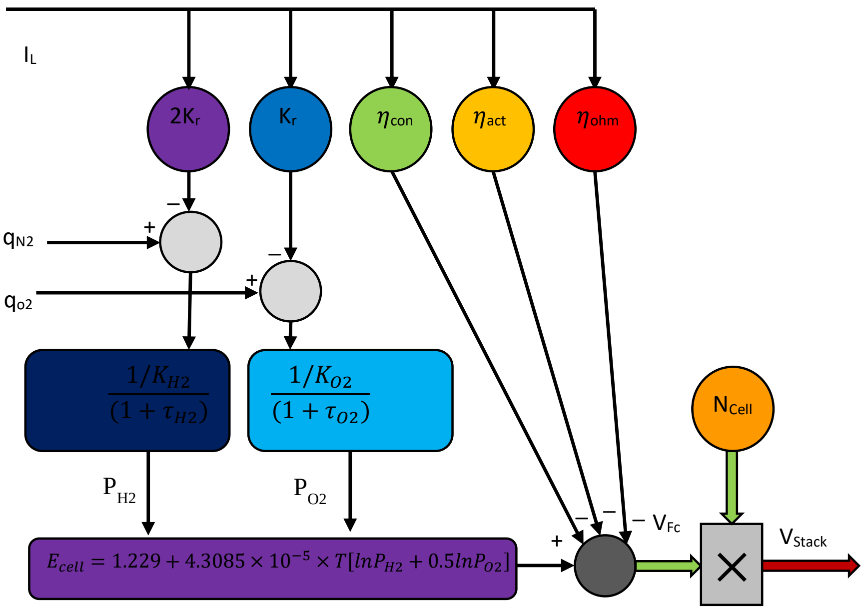

Fig. 3. The PEMFC dynamic behavior.

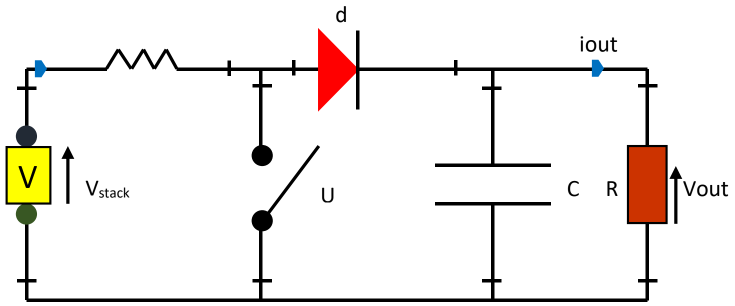

Fig. 4. The design of the DC/DC boost converter circuit.

$$P_{H_2} = \frac{1/K_{H_2}}{(1+\tau_{H_2})}(q_{H_2} - 2I.K_r) \tag{4}$$

$$P_{O_2} = \frac{1/K_{O_2}}{(1+\tau_{O_2})}(q_{O_2} - I.K_r) \tag{5}$$

where:

$$\begin{cases} \tau_{H_2} = \dfrac{V_{an}}{R.T.K_{H_2}} \\ \tau_{O_2} = \dfrac{V_{an}}{R.T.K_{O_2}} \end{cases} \tag{6}$$

K_{H_2} indicates the valve molar constant for hydrogen $(kmol/s\ atm)$, K_{O_2} implies the valve molar constant of oxygen $(kmol/s\ atm)$, q_{H_2} specifies the hydrogen flow rate, q_{O_2} states the oxygen flow rate, τ_{H_2} is the response time of hydrogen (s), τ_{O_2} specifies the response time of oxygen (s), K_r states a modeling parameter constant $(kmol/(sA))$, and V_{an} is the volume of the anode.

Now, after obtaining a detailed description of the behavior of the PEM fuel cell, it is necessary to present the dynamic model of the DC/DC boost converter. This converter delivers the input voltage from the PEM fuel cell to the output at a higher level and its schematic is shown in Figure 4.

This converter consists of a DC or PEM voltage source, a transistor switch, an inductance, a diode switch, a filter capacitor, and an ohmic load, and through the u switch, the output is as follows:

$$V_{out} = \left(\frac{1}{1-u}\right).V_{stack} \tag{7}$$

This boost converter has two working modes, when u is on and d is off, the dynamic equations governing the inductance current and output voltage are as follows:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(V_{stack}) \\ \dfrac{dV_{out}}{dt} = \dfrac{1}{C}(-i_{out}) \end{cases} \tag{8}$$

In the second working mode, d is on and u is off, and the dynamic equations of inductance current and output voltage are equal to:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(V_{stack} - V_{out}) \\ \dfrac{dV_{out}}{dt} = \dfrac{1}{C}(i_L - i_{out}) \end{cases} \tag{9}$$

By considering the inductance current and output voltage in place of state variables together with $V_{stack} = v$, the state space equations for the boost converter are as equation (10):

$$\begin{cases} \dot{x} = \begin{pmatrix} 0 & \dfrac{u-1}{L} \\ \dfrac{1-u}{C} & -\dfrac{1}{RC} \end{pmatrix} x + \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix} v \\ y = [0 \quad 1]x \end{cases} \tag{10}$$

Table 1. ***The parameters of PEM fuel cell.***

Symbol	Value	Unit
E_0	1.229	V
R	83.143	$J\,mol^{-1}K^{-1}$
F	96485.309	$C\,mol^{-1}$
T	298.15	K
A	162	c
ψ	23	
l	175.10^{-6}	cm
B	0.1	V
R_c	0.0003	
J_{max}	0.062	$A\,cm^{-1}$
N_{cell}	10	
ξ_1	0.9514	V
ξ_2	-0.00312	V/K
ξ_3	$-7.4.10^{-5}$	V/K
ξ_4	$1.87.10^{-4}$	V/K

The parameters of the PEM fuel cell are specified in Table 1. More information about the model can be found in references [39-42].

3. PROPOSED ROBUST JOINT RESET ADAPTIVE SUPER TWISTING SLIDING MODE CONTROLLER

This section describes an innovative control scheme for extracting optimal power from the fuel cell system and stabilizing the output voltage from the fuel cell stack equipped with a boost converter. Two main approaches form the basis of the proposed hybrid controller: one is the reset robust technique and the second is the adaptive sliding mode method. The reset technique is placed in the inner loop of the controller, and the reason for using it is the high capability of removing the tracking error in the steady state, achieving the regulatory goal with high speed, and of course, improving the dynamic response of the closed loop system and overcoming the limitations of linear controllers. With such characteristics, this technique is able to deal with the controller error, system instability caused by the non-minimum phase nature of the DC/DC boost converter, and of course, it is able to reduce the adverse effects caused by model uncertainty and input disturbances to the PEM fuel cell stack system. The outer loop of the controller consists of the adaptive sliding mode method. The sliding mode method along with the adaptive scheme are the most important robust techniques to deal with the changes in model parameters and of course to deal with external disturbances on the system. Considering the working environment of the fuel cell system, which is exposed to the most severe uncertainties, environmental changes, and external disturbances, this paper presents a new control method for extracting the maximum power from the fuel cell stack by combining the robust reset and adaptive sliding mode methods. At the same time, by guaranteeing the stability of the closed-loop system despite the uncertainty with an unknown upper bound, it also satisfies the zero error of inductance current tracking. The structure of the controller is shown in Figure 5.

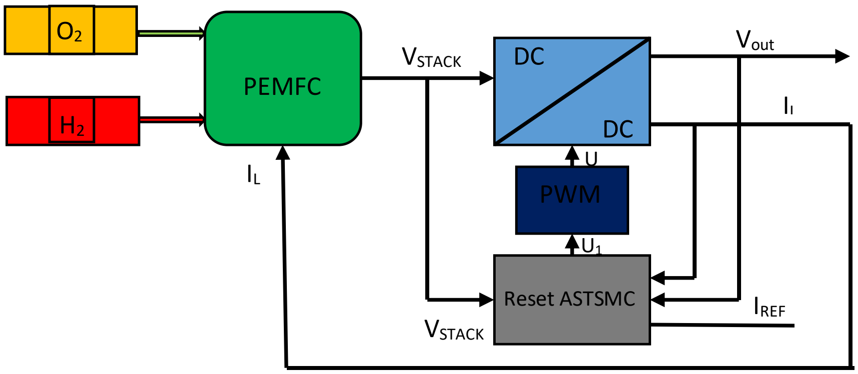

Fig. 5. The structure of the planned control approach for the PEMFC stack power system.

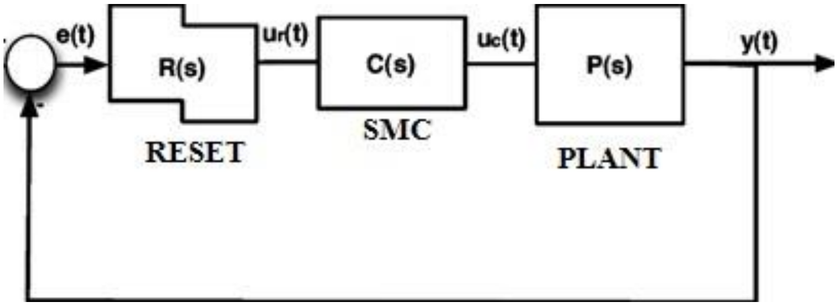

Fig. 6. The structure of the planned hybrid control approach.

By taking into account V_{stack}, i_{ref}, i_L and V_{out}, the innovative approach makes the necessary control over the boost converter and achieves the preferred i_L and V_{out}.

The non-minimum phase means that it is impossible to directly adjust the output voltage of the DC-DC boost converter and the stability of the converter is compromised by using direct controllers (of any kind) on this type of converter. The above problem can be effectively solved by using planned reset and SMC controllers. These controllers integrate the converter output voltage error (asymptotic convergence) and therefore can compensate for the non-minimum phase converter. They are also well robust to load disturbances, input voltage variations, and parameter uncertainty. Therefore, a reset SMC controller is planned here and described in detail below. The structure of the planned hybrid control approach is shown in Figure 6.

We now define the controller design steps. By applying the reset technique, the dynamic state of the output voltage is as follows:

$$V_{ref} = k_P\left(x_1 - i_{ref}\right) + k_I \int\left(x_1 - i_{ref}\right)dt + \kappa_{iReset} \int_{Reset}\left(x_1 - i_{ref}\right)dt \tag{11}$$

where k_P, k_I and κ_{iReset} indicate the controller gains and the controller state variables are selected as follows:

$$\begin{aligned} z_1 &= x_1 - i_{ref} \\ z_2 &= x_2 - V_{ref} \end{aligned} \tag{12}$$

In relation to Equation (10), the dynamics of the controller state variables are

$$\begin{aligned} \dot{z}_1 &= \frac{1}{L}(V - x_2) + \frac{1}{L}u \\ \dot{z}_2 &= \frac{1}{C}x_1 - \frac{1}{R_C}x_2 - \frac{k_P}{L}(V - x_2) \\ &\quad - k_I\left(x_1 - i_{ref}\right) \\ &\quad - \left(\frac{1}{C} + \frac{k_P}{L}\right)u \end{aligned} \tag{13}$$

Also, the selection of sliding switching surface is as

$$S(z) = k_P\left(x_1 - i_{ref}\right) + k_I \int\left(x_1 - i_{ref}\right)dt + \kappa_{iReset} \int_{Reset}\left(x_1 - i_{ref}\right)dt \tag{14}$$

To reach the control goal by using the adaptive sliding mode technique, it is essential that the next condition is seen for the sliding surface

$$\frac{dS}{dt} = 0 \tag{15}$$

By considering Equation (13), Equation

(15) becomes as

$$\dot{S} = k_P\left(\frac{1}{L}(V - x_2) + \frac{1}{L}u\right) + k_I\left(x_1 - i_{ref}\right) + \kappa_{iReset}\left(\int_{Reset}\left(x_1 - i_{ref}\right)dt\right)' = w(x,v,u) + u \tag{16}$$

where

$$w(x,v,u) = k_I\left(x_1 - i_{ref}\right) + \kappa_{iReset}\left(\int_{Reset}\left(x_1 - i_{ref}\right)dt\right)' + \frac{k_P}{L}(V - x_2) + \frac{k_P - L}{L}u \tag{17}$$

Lyapunov scheme is schooled to guarantee stability and discover the suitable control signal to reach the control goals. Lyapunov's candidate function is chosen as Equation (18)

$$V = |S| + \frac{1}{2\lambda}\widetilde{W}^2 \tag{18}$$

where λ indicates the parameter of adaptive rule regulation. Also $\widetilde{W}$ specifies the error between W and $\widehat{W}$

$$|w(x,v,u)| < W \tag{19}$$

where W states the unknown upper bound of $w(x,v,u)$ and $\widehat{W}$ specifies the upper bound estimation. By deriving from the Lyapunov function (18), it is obtained

$$\dot{V} = \dot{S}sign(S) - \frac{1}{\lambda}\widetilde{W}\dot{\widehat{W}} \tag{20}$$

It is now found by insertion of equation (16) into equation (27)

$$\dot{V} = (w(x,v,u) + u)sign(S) - \frac{1}{\lambda}\widetilde{W}\dot{\widehat{W}} \tag{21}$$

A super twisting algorithm has been used to overcome the chattering phenomenon. One of the interesting features of the super twisting algorithm is that it does not need the sliding plate information during the online operation. The control law consists of two terms. One is the integral which is a discontinuous control action and the other is a continuous function of the sliding plane and the effective control u for this algorithm consists of two terms.

Now, by selecting the control input as follows:

$$u = -k_1\int sign(S)dt - k_2|S|^{0.5}sign(S) - \widehat{W} \tag{22}$$

It is now obtained by placing (22) in equation (21)

$$\dot{V} = \left(w(x,v,u) - k_1\int sign(S)dt - k_2|S|^{0.5}sign(S) - \widehat{W}\right)sign(S) - \frac{1}{\lambda}\widetilde{W}\dot{\widehat{W}} = -(k_1 t + k_2|S|^{0.5})sign(S)^2 + \left(w(x,v,u) - \widehat{W}\right)sign(S) - \frac{1}{\lambda}\widetilde{W}\dot{\widehat{W}} \tag{23}$$

Equation (23) can be modified as follows

$$\dot{V} \leq -(k_1 t + k_2|S|^{0.5})sign(S)^2 + sign(S)\left(W - \widehat{W}\right) - \frac{1}{\lambda}\widetilde{W}\dot{\widehat{W}} \tag{24}$$

To obtain the adaptive rule, we rewrite Equation (24) as follows

$$\dot{V} \leq -(k_1 t + k_2|S|^{0.5})sign(S)^2 + \widetilde{W}\left(sign(S) - \frac{1}{\lambda}\dot{\widehat{W}}\right) \tag{25}$$

In relation to (25), to eliminate the adaptive error $\widetilde{W}$, its coefficient should be zero. For this goal, the adaptive rule is found as follows

$$\dot{\hat{W}} = \lambda sign(S) \quad (26)$$

It is achieved by placing equation (26) in (25)

$$\dot{V} \leq -(k_1 t + k_2 |S|^{0.5}) sign(S)^2 \quad (27)$$

Equation (27) indicates that by the control signal of Equation (22) and the adaptive law (26), the closed-loop system is stable and the realization of control objectives is assured. In the next part, simulation in the MATLAB software environment will be used to show the controller's ability.

4. SIMULATION RESULTS

This part describes the results obtained from the implementation of the planned reset adaptive super twisting sliding mode controller (RASTSMC) on a fuel cell stack system equipped with a boost converter. Practical implementation and simulation in the computer environment are two main pillars for evaluating the efficiency of control methods, and in this study, simulation in the MATLAB environment and comparison with a similar valid method have been done to assess the efficiency of the proposed control technique, and of course, the practical implementation of the proposed structure forms the next phase of the authors' research and studies. The hardware used for the simulation is Intel Core i7-10750H, 16GB DDR4 RAM, 512GB SSD, NVIDIA GeForce RTX 2060 6GB GDDR6, and for comparison, the proportional integral-adaptive sliding mode control (PI-ASMC) method is considered from reference [39].

Parameters related to PEM fuel cell components, number of cells in the stack, membrane cross-sectional area, stack operating temperature, PEM cell pressure, boost converter specifications, and reference current are all adapted from [39].

$$k_P = 0.5, k_I = 40, \kappa_{iReset} = 0.01, \lambda = 0.01, k_1 = 1, k_2 = 1$$

For the evaluation of the controller, the same load variation with reference [39] is considered as uncertainty and is shown in Figure 7. With the knowledge that under the parameters used for the fuel cell, the optimal current rate for extracting the maximum power is $i_L = 9.74\,(A)$ and despite the disturbance and the unsteady dynamics of the converter, this current should be followed, the simulation results are given in Figures 8 to 10.

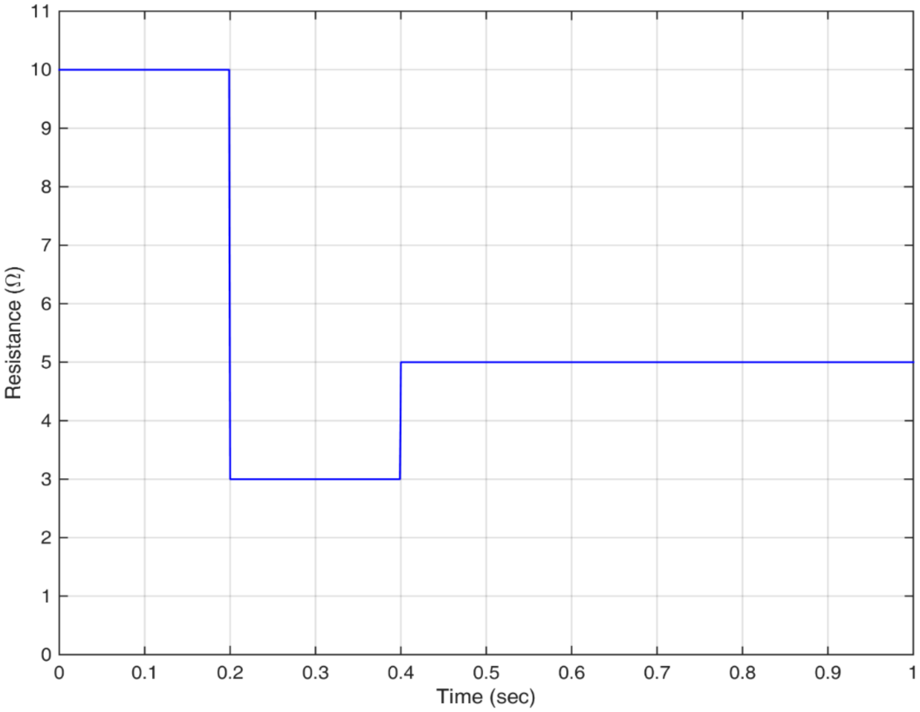

Fig. 7. Considered Load variations in the simulation scenario.

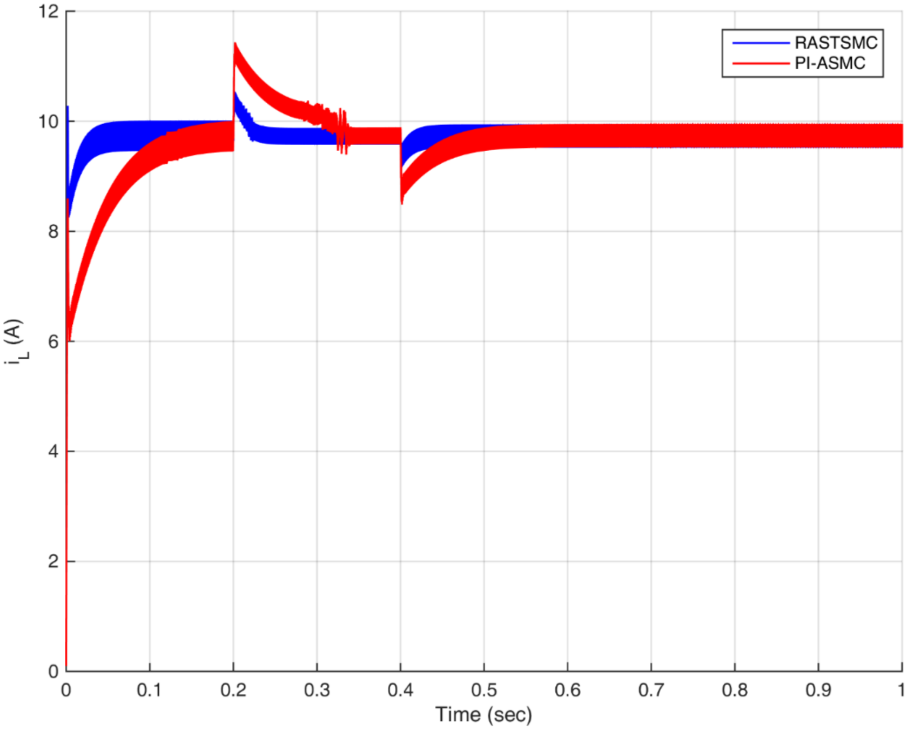

Fig. 8. DC/DC boost converter output current under PI-ASMC and RASTSMC controllers.

Table 2. ***Specifications of the i_L error value.***

Controller	i_L			
	ISE	**ITSE**	**IAE**	**ITAE**
PI-ASMC	0.086	0.0115	0.136	0.0548
RASTSMC	0.4686	0.0514	0.4095	0.1271

Figure 8 shows the amount of i_L under two RASTSMC and PI-ASMC methods. Under the planned technique, faster tracking of the optimal i_L , less fluctuations and lower overshoot and undershoot are among the important advantages, and of course, under the PI-ASMC method, the system response shows an unfavorable situation from the perspective of transient and permanent behavior. The amount of i_L error obtained under different error criteria shown in Table 2 indicates the higher capability of the planned technique in tracking the optimal i_L current and the steady state behavior is much better than the PI-ASMC method.

The output voltage from the DC/DC boost converter under the suggested technique and the PI-ASMC scheme is shown in Figure 9. As it is clear from Figure 9, lower settling time, higher speed and lower fluctuations are among the advantages of the RASTSMC technique in the output voltage from the boost converter.

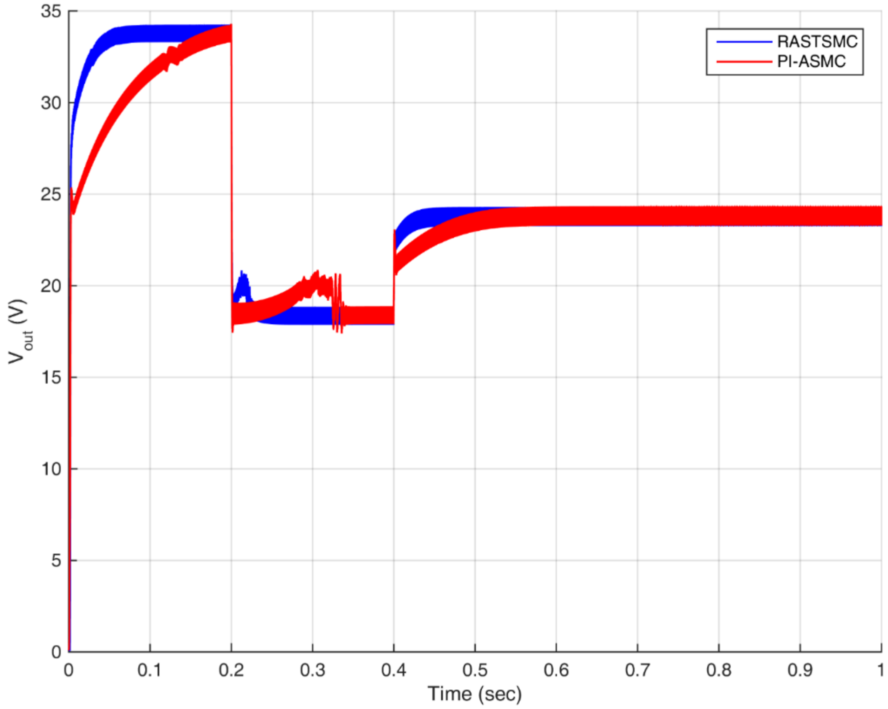

Fig. 9. DC/DC boost converter output voltage under PI-ASMC and RASTSMC controllers.

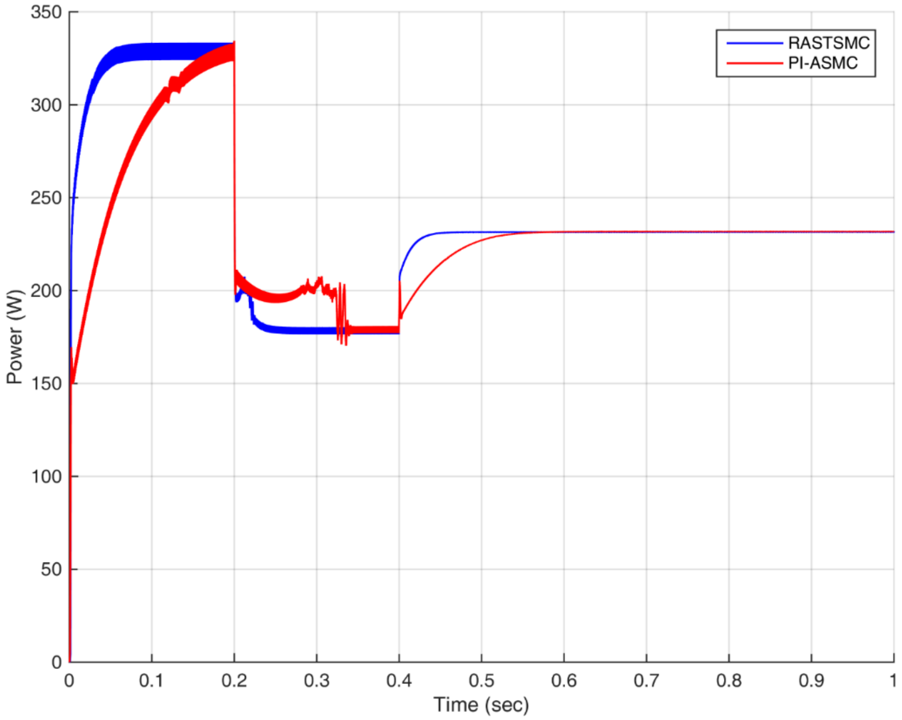

Fig. 10. DC/DC boost converter output power under PI-ASMC and RASTSMC controllers.

Finally, Figure 10 also shows the amount of output power from a fuel cell equipped with a boost converter. Achieving optimal power with less settling time, higher speed, fewer fluctuations, and lower tracking error are among the advantages of the planned RASTSMC technique. From the simulation results, it is clear that the planned technique is well able to extract the optimal power from the fuel cell stack and despite the non-minimum phase nature of the boost converter, disturbances and uncertainties, and environmental changes, optimal load current tracking and guaranteeing the optimal operation of the fuel cell system are obtained under the planned control scheme.

5. CONCLUSION

This paper presented a novel hybrid robust scheme for extracting maximum power from PEM fuel cell renewable energy source. The suggested reset in addition to the adaptive sliding mode method was able to adjust the output voltage and load current optimally, while it showed the improvement of transient and sustained dynamic response from the perspective of settling time, overshoot and undershoot, tracking speed, and of course tracking error. Also, all improvements were made despite the presence of uncertainties, disturbances, and load change effects. In addition, the comparison with the PI adaptive sliding mode method showed that the output power and voltage with a more stable state and fewer fluctuations were obtained using the planned technique from the PEM fuel cell stack. Further studies can be in the field of practical implementation of robust controllers on the studied structure, design of high-power fuel cell stack using additive manufacturing techniques, and of course intelligentization of the planned control scheme using fuzzy and neural network techniques

REFERENCES

[1] Felseghi, R. A., Carcadea, E., Raboaca, M. S., Trufin, C. N., & Filote, C. (2019). Hydrogen fuel cell technology for the sustainable future of stationary applications. *Energies*, *12*(23), 4593.

[2] Cigolotti, V., Genovese, M., & Fragiacomo, P. (2021). Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems. *Energies*, *14*(16), 4963.

[3] Akinyele, D., Olabode, E., & Amole, A. (2020). Review of fuel cell technologies and applications for sustainable microgrid systems. *Inventions*, *5*(3), 42.

[4] Aminudin, M. A., Kamarudin, S. K., Lim, B. H., Majilan, E. H., Masdar, M. S., & Shaari, N. (2023). An overview: Current progress on hydrogen fuel cell vehicles. *International Journal of Hydrogen Energy*, *48*(11), 4371-4388.

[5] Sürer, M. G., & Arat, H. T. (2022). Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. *International Journal of Hydrogen Energy*, *47*(45), 19865-19875.

[6] İnci, M. (2022). Future vision of hydrogen fuel cells: A statistical review and research on applications, socio-economic impacts and forecasting prospects. *Sustainable Energy Technologies and Assessments*, *53*, 102739.

[7] Katalenich, S. M., & Jacobson, M. Z. (2022). Toward battery electric and hydrogen fuel cell military vehicles for land, air, and sea. *Energy*, *254*, 124355.

[8] Jamil, A., Rafiq, S., Iqbal, T., Khan, H. A. A., Khan, H. M., Azeem, B., ... & Hanbazazah, A. S. (2022). Current status and future perspectives of proton exchange membranes for hydrogen fuel cells. *Chemosphere*, *303*, 135204.

[9] Cheng, X., Shi, Z., Glass, N., Zhang, L., Zhang, J., Song, D., ... & Shen, J. (2007). A review of PEM hydrogen fuel cell contamination: Impacts, mechanisms, and mitigation. *Journal of Power Sources*, *165*(2), 739-756.

[10] Salam, M. A., Habib, M. S., Ahmed, K., Uddin, M. S., Hossain, T., Papri, N., & Arefin, P. (2020). Effect of temperature on the performance factors and durability of proton exchange membrane of hydrogen fuel cell: A narrative review. *Material Science Research India (Online)*, *17*(2), 179-191.

[11] Amirinejad, M., Rowshanzamir, S., & Eikani, M. H. (2006). Effects of operating parameters on performance of a proton exchange membrane fuel cell. *Journal of Power Sources*, *161*(2), 872-875.

[12] Veeranjaneyulu, K., Joshi, S., Devalla, V., Kiran, K. S., & Khushal, K. (2023, May). Recent advancements of PEMFC in transport applications. In *AIP Conference Proceedings* (Vol. 2492, No. 1). AIP Publishing.

[13] Olabi, A. G., & Abdelkareem, M. A. (2022). Renewable energy and climate change. *Renewable and Sustainable Energy Reviews*, *158*, 112111.

[14] Nosratabadi, S. M., Hemmati, R., Bornapour, M., & Abdollahpour, M. (2021). Economic evaluation and energy/exergy analysis of PV/Wind/PEMFC energy resources employment based on capacity, type of source and government incentive policies: Case study in Iran. *Sustainable Energy Technologies and Assessments*, *43*, 100963.

[15] Rivarolo, M., Rattazzi, D., Lamberti, T., & Magistri, L. (2020). Clean energy production by PEM fuel cells on tourist ships: A time-dependent analysis. *International Journal of Hydrogen Energy*, *45*(47), 25747-25757.

[16] Ota, K., & Koizumi, Y. (2010). Platinum dissolution models and voltage cycling effects: platinum dissolution in polymer electrolyte fuel cell (PEFC) and low-temperature fuel cells. *Handbook of Fuel Cells*.

[17] Harzer, G. S., Schwämmlein, J. N., Damjanović, A. M., Ghosh, S., & Gasteiger, H. A. (2018). Cathode loading impact on voltage cycling induced PEMFC degradation: a voltage loss analysis. *Journal of The Electrochemical Society*, *165*(6), F3118-F3131.

[18] Albarbar, A., & Alrweq, M. (2017). *Proton exchange membrane fuel cells: Design, modelling and performance assessment techniques*. Springer.

[19] Dicks, A. L., & Rand, D. A. (2018). *Fuel cell systems explained*. John Wiley & Sons.

[20] Messing, M., & Kjeang, E. (2020). Empirical modeling of cathode electrode durability in polymer electrolyte fuel cells. *Journal of Power Sources*, *451*, 227750.

[21] İnci, M., Büyük, M., Demir, M. H., & İlbey, G. (2021). A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects. *Renewable and Sustainable Energy Reviews*, *137*, 110648.

[22] Kirubakaran, A., Jain, S., & Nema, R. K. (2009). A review on fuel cell technologies and power electronic interface. *Renewable and sustainable energy reviews*, *13*(9), 2430-2440.

[23] Daud, W. R. W., Rosli, R. E., Majlan, E. H., Hamid, S. A. A., Mohamed, R., & Husaini, T. (2017). PEM fuel cell system control: A review. *Renewable Energy*, *113*, 620-638.

[24] Derbeli, M., Charaabi, A., Barambones, O., & Sbita, L. (2019, March). Optimal Energy Control of a PEM Fuel Cell/Battery Storage System. In *2019 10th International Renewable Energy Congress (IREC)* (pp. 1-5). IEEE.

[25] Mohammadi, A., Guilbert, D., Gaillard, A., Bouquain, D., Khaburi, D., & Djerdir, A. (2013, November). Faults diagnosis between PEM fuel cell and DC/DC converter using neural networks for automotive applications. In *IECON 2013-39th Annual*

Conference of the IEEE Industrial Electronics Society (pp. 8186-8191). IEEE.

[26] Demir, M. H., & Demirok, M. (2023). Designs of particle-swarm-optimization-based intelligent PID controllers and DC/DC Buck converters for PEM fuel-cell-powered four-wheeled automated guided vehicle. *Applied Sciences*, *13*(5), 2919.

[27] Abaspour, A., Parsa, N. T., & Sadeghi, M. (2014). A new feedback Linearization-NSGA-II based control design for PEM fuel cell. *International Journal of Computer Applications*, *97*(10).

[28] Kart, S., Demir, F., Kocaarslan, İ., & Genc, N. (2023). Increasing PEM fuel cell performance via fuzzy-logic controlled cascaded DC-DC boost converter. *International Journal of Hydrogen Energy*.

[29] Safwat, I. M., Wu, X., Zhao, X., & Li, W. (2017, August). Adaptive fuzzy logic control of boost converter fed by stand-alone PEM fuel cell stack. In *2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)* (pp. 1-6). IEEE.

[30] Ma, R., Wu, Y., Breaz, E., Huangfu, Y., Briois, P., & Gao, F. (2018, September). High-order sliding mode control of DC-DC converter for PEM fuel cell applications. In *2018 IEEE Industry Applications Society Annual Meeting (IAS)* (pp. 1-7). IEEE.

[31] Derbeli, M., Farhat, M., Barambones, O., & Sbita, L. (2017). Control of PEM fuel cell power system using sliding mode and super-twisting algorithms. *International journal of hydrogen energy*, *42*(13), 8833-8844.

[32] Akter, F., Roy, T. K., Islam, M. S., Alkhateeb, A. F., & Mollah, M. A. (2022). Design of a nonlinear integral terminal sliding mode controller for a pem fuel cell based on a dc-dc boost converter. *IEEE Access*, *10*, 97419-97428.

[33] Belhaj, F. Z., El Fadil, H., Tahri, A., Gaouzi, K., Rachid, A., & Giri, F. (2017, November). Sliding mode control of a cascade boost converter for fuel cell energy generation system. In *2017 International Conference on Electrical and Information Technologies (ICEIT)* (pp. 1-6). IEEE.

[34] Tan, S. C., Lai, Y. M., Tse, C. K., & Cheung, M. K. (2004, February). An adaptive sliding mode controller for buck converter in continuous conduction mode. In *Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2004. APEC'04.* (Vol. 3, pp. 1395-1400). IEEE.

[35] Tan, S. C., Lai, Y. M., Cheung, M. K., & Tse, C. K. (2005). On the practical design of a sliding mode voltage controlled buck converter. *IEEE transactions on power electronics*, *20*(2), 425-437.

[36] Tan, S. C., Lai, Y. M., Tse, C. K., & Cheung, M. K. (2006). Adaptive feedforward and feedback control schemes for sliding mode controlled power converters. *IEEE Transactions on Power Electronics*, *21*(1), 182-192.

[37] Cid-Pastor, A., Martinez-Salamero, L.,

El Aroudi, A., Giral, R., Calvente, J., & Leyva, R. (2013). Synthesis of loss-free resistors based on sliding-mode control and its applications in power processing. *Control Engineering Practice*, *21*(5), 689-699.

[38] López-Lapeña, O., Penella, M. T., & Gasulla, M. (2009). A new MPPT method for low-power solar energy harvesting. *IEEE Transactions on industrial electronics*, *57*(9), 3129-3138.

[39] Gao, J., Yang, Y., & Gu, H. (2021). Improving the output power of PEM fuel cell with PI+ ASM combined controller designed for boost converter. *Journal of New Materials for Electrochemical Systems*, *24*(4).

[40] Uzunoglu, M., & Alam, M. S. (2006). Dynamic modeling, design, and simulation of a combined PEM fuel cell and ultracapacitor system for stand-alone residential applications. *IEEE transactions on energy conversion*, *21*(3), 767-775.

[41] Wang, C., Nehrir, M. H., & Shaw, S. R. (2005). Dynamic models and model validation for PEM fuel cells using electrical circuits. *IEEE transactions on energy conversion*, *20*(2), 442-451.

[42] Yigit, T., & Selamet, O. F. (2016). Mathematical modeling and dynamic Simulink simulation of high-pressure PEM electrolyzer system. *International Journal of Hydrogen Energy*, *41*(32), 13901-13914.