DESIGN AND SIMULATION OF HYBRID THERMAL ENERGY STORAGE CONTROL FOR PHOTOVOLTAIC FUEL CELLS

by

Xiaomin FANG[a*] and Xiaolu LI[b]

[a] Quzhou College of Technology, Quzhou, China
[b] China Jiliang University, Hangzhou, China

Original scientific paper
https://doi.org/10.2298/TSCI2302031F

In order to meet the demand of stable and continuous household electricity consumption, the author proposes the modelling and simulation of photovoltaic fuel cell hybrid power generation system. The system is composed of photovoltaic power generation device, fuel cell/super capacitor, electrolytic cell, hydrogen storage device and power regulation unit. As photovoltaic power generation is affected by sunshine changes, the combination of fuel cells and super capacitors with photovoltaic devices can ensure the stability and reliability of power supply of hybrid power generation system. Taking sunshine intensity and household electricity consumption in a certain area as an example, the system is simulated in MATLAB/SIMULINK software. The results show that: At 08:30-17:00, the output power of the fuel cell is almost zero. This is because the electric energy output by the photovoltaic power generation system can basically meet the power demand of users during this period. At 00:00-6:00 and 18:30-24:00, the sunlight intensity is zero, and the power output of the photovoltaic power generation system is zero, at this time, the user's electricity is completely supplied by the fuel cell. The investment cost of 1 kW fuel cell is about 45258.4 yuan, and that of 1 kW ordinary battery is about 15200 yuan, the investment cost of fuel cell is still high. In conclusion, the hybrid power generation system can meet the demand of ordinary household electricity.

Key words: *photovoltaic, fuel cell, electricity generation, modellingm simulation*

Introduction

It is estimated that about two billion people in rural areas of developing countries lack power supply. In many areas, due to the dispersed population and inconvenient transportation, power cannot be supplied by extending the power grid, and diesel power generation is expensive, however, these areas often have rich solar energy resources, so establishing small and independent solar photovoltaic power stations in these areas will be the best choice to solve the power supply problem in these areas. Solar photovoltaic power generation has many advantages:
- Simple structure, small size and light.
- Easy to install, easy to transport and short construction period.
- Easy to start and maintain. Use at any time to ensure supply.
- Clean and safe, no noise. No waste is discharged to the outside and no rotating parts are available.
- High reliability and long service life.

* Corresponding author, e-mail: fxm_1985@126.com

As long as the design is reasonable, the battery life can reach 10 years if the type is appropriate [1]. The main disadvantage of solar energy is that it has low energy density and is unstable due to weather, time and other factors. Therefore, it is very difficult for human beings to use solar energy. Due to different objects and conditions of solar energy use, solar energy storage methods are different, mainly including thermal energy, biomass energy, mechanical energy, electrical energy, chemical energy, *etc*. Among them, chemical energy storage is to utilize hydrogen generated by solar energy, which is a valuable method, namely *solar hydrogen energy syste*m [2].

In order to further develop the solar hydrogen power system, it is necessary to develop advanced hydrogen burning power devices, so as to use energy efficiently and cleanly. When hydrogen burns in the air, its products contain nitrogen oxides that will pollute the environment. When fuel cells burn hydrogen, the product is only water, which has no impact on the environment, therefore, it is ideal to develop hydrogen fuel cells [3]. The combined use of solar fuel cells is actually the energy transmission chain of solar energy – hydrogen energy – fuel cells electric energy – users. Among them, fuel cells play a key role. Taking advantage of the advantages of solar energy and fuel cell, the author designed a solar fuel cell combined power generation system [4]. First, ease the energy crisis and reduce the consumption of fossil fuels. Solar energy is inexhaustible and is one of the most widely used RES. Fuel cell fuel is widely used, which can use hydrogen rich fuels such as natural gas, methanol, biogas, and gas. Therefore, the combination of fuel cells and solar energy can alleviate the current crisis caused by the reduction of traditional energy sources such as oil and coal. Second, it is environmentally friendly and reduces air pollution. Solar energy and fuel cells are both clean and safe energy sources, no exhaust gas and harmful gases are emitted during power generation, which greatly reduces the pollution of traditional fossil energy to the atmosphere [5]. At the same time, the low noise characteristics of solar energy and fuel cells enable the combined system to be installed near or at the center of the load, it will not affect people's normal work and rest. Third, efficient and reliable, and high energy utilization. Single solar power supply, with low energy density, scattered resources and large power loss, is difficult to meet the load requirements. Therefore, the combination of fuel cells and solar energy has broad application prospects [6].

Literature review

Zeiske *et al*. [7] put forward an iterative search method based on system simulation and monthly and annual distribution of photovoltaic power, wind energy and load, which makes the economic performance and technical performance of PV/WT/BAT system reach the optimum at the same time. Fan *et al*. [8] also reported the design method of similar hybrid systems. Cui *et al*. [9] proposed to use genetic algorithm to simultaneously optimize the control parameters and system configuration of photovoltaic diesel power generation system. Singh *et al*. [10] designed andanalyzed three different hybrid power generation systems: WT/FC/BAT, PV/FC/BAT, and Micro Hydro/FC/BAT. Ferriday *et al*. [11] established the performance prediction model of WT/FC/UC hybrid autonomous power generation system and proposed an iterative search design method based on system simulation for power generation system. In addition, they also established a performance prediction model of PV/FC/UC hybrid autonomous generation system, described a priority based scheduling control strategy, and analyzed the performance of the hybrid generation system. Zhang *et al*. [12] established a mathematical model including PV/FC/BAT hybrid autonomous power generation system, proposed a design strategy and control strategy similar to the work of Uzunaglu, and simulated, analyzed and compared the economic and technical performance of PV/BAT, PV/FC, and PV/FC/BAT hybrid autonomous power generation systems. Although many methods have been proposed for the design of hybrid power generation systems in relevant literature, they are not suitable for photovoltaic fuel cell hybrid power generation systems with hydrogen energy storage and super capacitor energy storage devices.

Research methods

Hybrid system structure and operation mode

Hybrid system structure

The structure of the photovoltaic fuel cell hybrid power generation system proposed by the author for home use is shown in fig. 1, the system mainly includes solar cell array, fuel cell/supercapacitor, electrolytic cell, hydrogen storage device, controllable boost converter, DC/AC inverter and transformer [13].

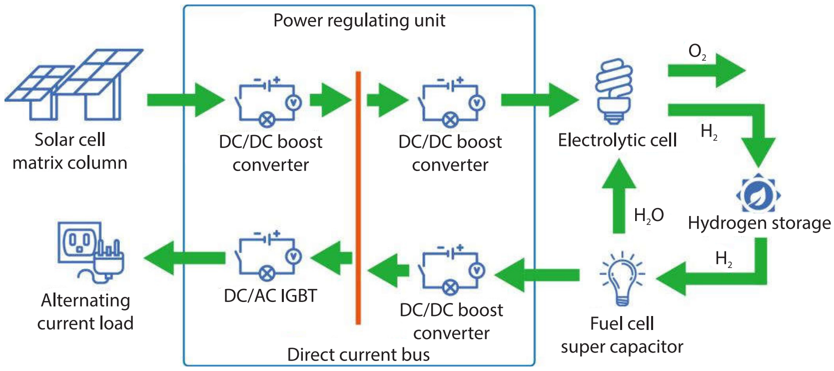


Figure 1. Photovoltaic-structure of fuel cell hybrid power generation system

In this system, the solar cell array is the core part, which directly converts solar energy into electrical energy for load use, and the rest of the electrical energy is supplied to the electrolytic cell for hydrogen production from electrolytic water, the hydrogen generated is stored in the hydrogen storage tank for fuel cell use [14]. It has great advantages to use fuel cells as backup power instead of using batteries to store energy in traditional photovoltaic power generation systems and provide electric energy, first of all, the power generation efficiency of the fuel cell mainly depends on the electrolyte, and the fuel is stored outside the cell, so its power generation efficiency will not be limited by the battery capacity, although the power generation efficiency of the battery itself is high, however, when the electric energy is converted, the efficiency will be seriously reduced due to energy loss, and the chemical energy in the battery will be stored in the positive and negative poles of the battery, so the power generation efficiency will be affected by the battery capacity. Secondly, the fuel cell has a high power conversion efficiency at full load, which can maintain a high conversion rate even when the load is reduced, while the battery will reduce the voltage and efficiency when discharging, which is difficult to meet the needs of residents when the electricity consumption changes. Finally, fuel cells are easier to operate than batteries and will not pollute the environment, so they are more suitable for auxiliary power generation of photovoltaic power generation systems [15]. Although the fuel cell has good power supply performance in steady-state operation, considering its relatively weak response to instantaneous and short-term peak power, some scholars proposed that the super capacitor can be connected in series with it, in case of low power requirements, the residual electric energy after the fuel cell supplies power to the load can be stored by the super capacitor. In case of high power requirements, the fuel cell will generate rated power, and at the same time, the super capacitor will discharge to meet the load demand, so that the fuel cell can obtain better performance without increasing the cost and size.

The power regulation unit includes boost type DC converter, DC/AC inverter, *etc*, it is mainly responsible for regulating the system to output ideal voltage and power for residents. Since the output current of the solar cell changes with the change of temperature and light intensity, and the output voltage of the fuel cell is uncontrollable low voltage DC due to its own characteristics, the output voltage of the battery can be adjusted to meet the stability requirements of household electricity through the DC converter or DC/AC inverter [16].

Operation mode of the system

Three working modes can be proposed for the system according to the power supply, environment and residential power consumption:
– Daytime mode, that is, in the day with sufficient sunlight, the solar power supply is sufficient to meet the residents' electricity demand, and the excess electric energy is supplied to the electrolytic cell for hydrogen production and storage for fuel cell use;
– Night mode, that is, when the solar power supply is insufficient during the day and night with insufficient sunlight, the fuel cell co-operates with photovoltaic power generation provide power to the load;
– Continuous rainy day mode, that is, when encountering continuous rainy weather, the system cannot meet the household electricity demand, it can be powered by the grid [17].

System modelling

The PV array model

The solar cell can be regarded as a constant current source under low load conditions, and the voltage drops to zero under high load conditions, so it is an ideal current source.

The current equation of single battery power generation state:

$$I_{\mathrm{pv}} = I_{\mathrm{ph}} - I_{\mathrm{o}}\left\{\exp\left[\frac{q\left(V_{\mathrm{pv}} + I_{\mathrm{pv}}R_{\mathrm{s}}\right)}{AKT}\right] - 1\right\} - \frac{V_{\mathrm{pv}}}{R_{\mathrm{sh}}} \tag{1}$$

where formula (1) and (2):

$$I_{\mathrm{o}} = I_{\mathrm{or}}\left(\frac{T}{T_{\mathrm{r}}}\right)^3 \exp\left[\frac{qE_{\mathrm{G}}}{KA}\left(\frac{1}{T_{\mathrm{r}}} - \frac{1}{T}\right)\right] \tag{2}$$

$$I_{\mathrm{ph}} = \frac{\left[I_{\mathrm{scr}} + k_i\left(T - T_{\mathrm{r}}\right)\right]\lambda}{100} \tag{3}$$

where I_L [A] is the photogenerated current, I_{d} [A] – the current flowing through diode, T_{r} [K] – the eference temperature, T [K] – the absolute temperature, K – the Boltzmann constant, E_{G} – the energy band gap energy, I_{ph} [A] – the photocurrent, I_{scr} [A] – the short circuit current, k_i [0. 0017 A°C^{-1}] – the temperature coefficient of short circuit current, and λ [mWcm^{-2}] – the sunshine intensity.

Fuel cell model

The basic principle of proton exchange membrane fuel cell (PEMFC) is that hydrogen reacts with oxygen to produce water and release electricity.

Generally, the open circuit voltage of PEMFC operating below 100 °C is about 1.2 V, however, due to the existence of activation overvoltage, V_{act}, ohmic overvoltage, V_{ohmic}, and concentration polarization voltage, V_{con}, voltage drop will occur [18].

Therefore, the single cell voltage, V_{cell}, of fuel cell is:

$$V_{cell} = E_{nemst} - V_{act} - V_{ohmic} - V_{con} \tag{4}$$

The Gibbs free energy varies with the change of pressure and temperature, the approximate equation of Gibbs free energy can be obtained from the empirical equation:

$$E = E^0 + \frac{RT}{2F}\ln\left(\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2 0}}\right) \tag{5}$$

The pressure in the formula is the gas partial pressure, generally, the gas pressure of cathode and anode is roughly the same. According to the entropy change value under the standard state, eq. (5) can be written:

$$E_{nemst} = 1.229 - 8.5\cdot 10^{-4}(T - 298.15) + 4.308\cdot 10^{-5} T\left[\ln\left(10^{-2} p_{H_2}\right) + 0.5\ln\left(10^{-2} p_{o_2}\right)\right] \tag{6}$$

where T [K] is the battery temperature, effective partial pressure of p_{H_2} – H_2, and effective partial pressure of p_{O_2} – O_2. The empirical equation of activation overvoltage:

$$V_{act} = -\left\{\xi_1 + \xi_2 T + \xi_3 T\left[\ln\left(c_{O_2}\right)\right] + \xi_4 T\left[\ln\left(I_{st}\right)\right]\right\} \tag{7}$$

where ξ_1, ξ_2, ξ_3, and ξ_4 are the empirical parameters of fuel cell system.

The c_{O_2} is the dissolved concentration of O_2 at the gas-liquid interface, according to Henry's theorem, the equation can be obtained:

$$c_{o_2} = \frac{p_{O_2}}{5.08\cdot 10^6 \exp\left(-\frac{498}{T}\right)} \tag{8}$$

Ohmic overvoltage is the loss caused by the resistance of the current through the entire circuit, which is mainly due to the equivalent impedance R^{proton} of the proton membrane that prevents the proton flow from passing through the proton membrane, and the electronic flow impedance $R^{electronic}$ that prevents the electrons from passing through the external circuit, of which the former plays a major role [19]:

$$V_{obmic} = V_{ohmic}^{electronic} + V_{ohmic}^{proton} = I_{st}\left(R^{electronic} + R^{proton}\right) \tag{9}$$

where $R^{electronic}$ is the electron flow impedance, which can be regarded as a constant when the battery temperature is 50-90 °C. The membrane impedance:

$$R^{proton} = \frac{\rho_M l}{A} \tag{10}$$

where ρ_M [Ωcm] is the membrane resistivity and l [cm] – the thickness of electrolyte membrane.

The membrane resistivity is:

$$\rho_M = \frac{181.6\left[1+0.03\left(\frac{I}{A}\right)+0.062\left(\frac{T}{303}\right)^2\left(\frac{I}{A}\right)^{2.5}\right]}{\left[\phi-0.634-3\left(\frac{I}{A}\right)\right]\exp\left[4.18\left(\frac{T-303}{T}\right)\right]} \tag{11}$$

Concentration over-voltage can be expressed:

$$V_{\text{con}} = -B\ln\left(1-\frac{I_{\text{den}}}{I_{\max}}\right) \tag{12}$$

where B is the equation coefficient, determined by the fuel cell itself and its working state, I_{den} [Acm^{-2}] – the actual current density of battery operation, and $I_{\max}$ [Acm^{-2}] – the maximum current density that the battery can reach during operation.

Result analysis

A SIMULINK simulation model is established for the hybrid system in MATLAB software, it includes photovoltaic power generation system model, fuel cell/supercapacitor model, electrolytic cell model, DC boost converter model and inverter model.

Determination of hybrid power generation system capacity

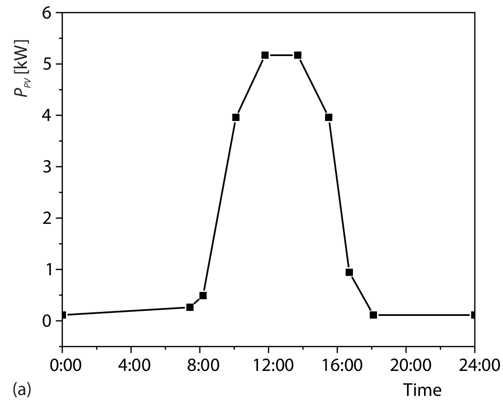
Taking the city as an example, according to the measurement data, the total efficiency of photovoltaic power generation is 4.2, the efficiency index of solar cells is 13.8, the average the solar energy in October is 4.9 kWh/m^2 per day, the average daily electricity consumption of the residents is 7.8 kWh per day, and the solar area of hand is 37.9 m^2. Estimated that the maximum power and power of the load is 3.0 kW and 0.5 kW, respectively, the rated power of the fuel cell is 3 kW, and the rated power of the electric power is 4.73 kW [20].

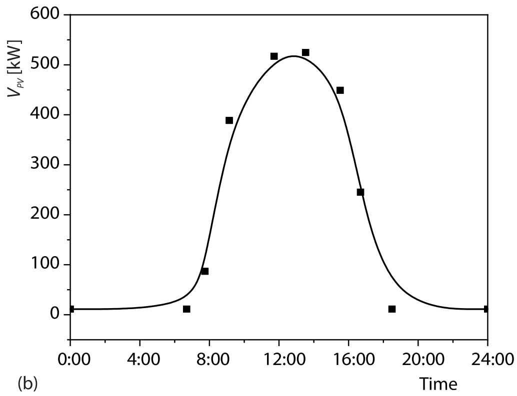
Analysis of system simulation results

In October 2020, the temperature of the school's solar laboratory is set at 25 °C, and the volt ampere characteristics of the solar cell change with the change of light, so the output voltage of the photovoltaic system is also changed. Because the energy load is different, when the energy produced by the photovoltaic system can meet the family's energy needs, the photovoltaic system will provide energy for the load itself, and the electric power more will be given to the electrolytic cell for hydrogen production and fuel cell storage [21]. The system is simulated under the conditions described by the author, and the simulation results are shown in figs. 2-4.

Figure 2(a)-2(c) shows the curve of the output power, voltage and current of the solar array as a function of time.

Figure 3 shows the curve of output voltage, voltage and current of fuel cell with time. It can be seen from fig. 3(a) that during 08:30-17:00, the power output of the fuel cell is almost zero. This is because the electricity produced by the photovoltaic power generation can meet the energy needs of the users at this time. It can be seen from the comparison of fig. 3(a) and fig. 2(a) that between 00:00-6:00 and 18:30-24:00, the solar energy is zero, and the energy production output of photovoltaic power generation is zero. At this time, the user's energy is provided entirely by the fuel cell [22].





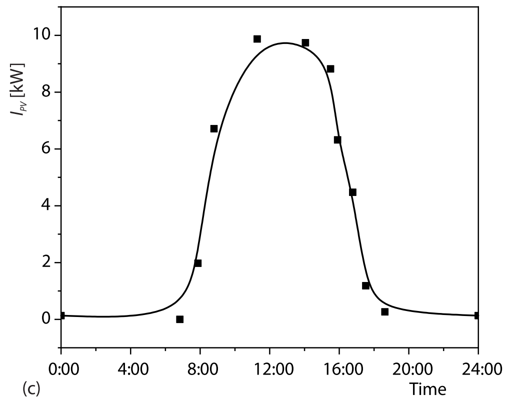


Figure 2. Time varying curve of output power, voltage and current of solar cell array; (a) outoutput power of solar array changes over time, (b) output voltage of the solar array changes over time, and (c) the solar array output current varies over time

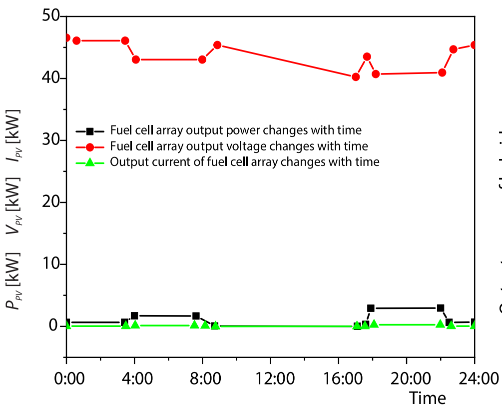


Figure 3. Time varying curve of fuel cell output power, voltage and current

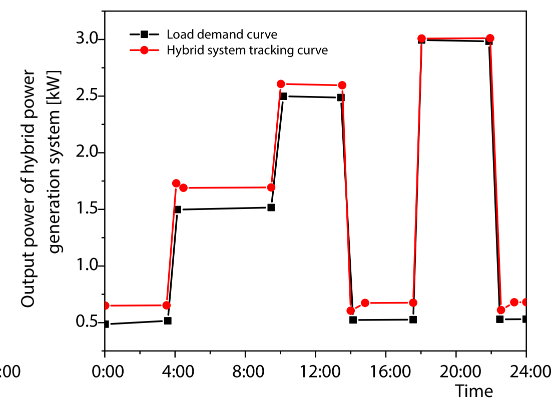


Figure 4. Response curve of output power of hybrid power generation system to load change

The response curve of the total output power of the photovoltaic fuel cell hybrid energy generator for the consumer switch is shown in fig. 4. It can be seen from the figure that the power of the hybrid electric power generation is the beginning to meet the energy load of the users. When the output of the solar cell cannot meet the demand of the load, the fuel can be improved and help the solar energy of hands, so that the system usually meets the daily energy needs of the residents and achieves good load [23].

System economic feasibility analysis

At present, China's photovoltaic power generation technology is relatively mature and widely used in household and civil applications. The investment cost of 1 kW fuel cell is about 45258.4 yuan, and that of 1 kW ordinary battery is about 15200 yuan, it can be seen that the investment cost of fuel cell is still high. From the previous analysis, it can be seen that there is still a high cost to apply photovoltaic fuel cell hybrid power generation for households at this stage. However, with the improvement of the efficiency of photovoltaic energy production and hydrogen production from electrolytic water and the reduction of the cost of proton exchange membrane fuel cells, the economic and social benefits of photovoltaic fuel cell hybrid power generation will become important. Because of its fast energy storage, long service life, no pollution and other characteristics, the system can be used in some special applications, such as the use of special military or military communications. Fuel cells produce clean water while generating electricity, so the system is also suitable for islands that do not have fresh water [24, 25].

Conclusion

The author has created a good model of the family photovoltaic fuel cell hybrid power design model, including photovoltaic power design model, fuel cell/supercapacitor model, electrolytic cell model, DC boost converter model and inverter model. Based on the real home power system, the power generation model is tested and evaluated in MATLAB/SIMULINK software. Experiments have shown that the use of fuel cells in electricity generation has a better ability to overcome the disadvantages of photovoltaic generation randomness of power generation. The hybrid system ensures good energy when the solar energy and the electric field change, and the electric power is reliable and stable. Finally, taking the Wuhan photovoltaic solar power plant and the local power plant as an example, it has been verified that the power generation capacity can meet the requirements of the family's energy transport.

References

[1] Singh, D., *et al*., Review on the Progress of Building-Applied/Integrated Photovoltaic System, *Environmental Science and Pollution Research*, *28* (2021), 35, pp. 47689-47724
[2] Jiang, J., *et al*., Flexo-Photovoltaic Effect in MoS2, *Nature Nanotechnology*, *16* (2021), 8, pp. 894-901
[3] Bi, P., Zhang., *et al.*, Reduced Non-Radiative Charge Recombination Enables Organic Photovoltaic Cell Approaching 19% Efficiency, *Joule*, 5 (2021), 9, pp. 2408-2419
[4] Libra, M., *et al*., Changes in the Efficiency of Photovoltaic Energy Conversion in Temperature Range with Extreme Limits, *IEEE Journal of Photovoltaics*, *11* (2021), 6, pp. 1479-1484
[5] Walzberg, J., *et al*., Role of the Social Factors in Success of Solar Photovoltaic Reuse and Recycle Programmes, *Nature Energy*, *6* (2021), 9, pp. 913-924
[6] Kruitwagen, L., *et al.*, A Global Inventory of Photovoltaic Solar Energy Generating Units, *Nature*, 598 (2021), 7882, pp. 604-610
[7] Zeiske, S., *et al*., Direct Observation of Trap-Assisted Recombination in Organic Photovoltaic Devices, *Nature Communications*, *12* (2021), Vol.12, No.1, pp. 1-7
[8] Fan, S., *et al*., A Novel Water-Free Cleaning Robot for Dust Removal from Distributed Photovoltaic (PV) in Water-Scarce Areas, *Solar Energy*, *241* (2022), 4, pp. 553-563
[9] Cui, Y., *et al*., Accurate Photovoltaic Measurement of Organic Cells for Indoor Applications, *Joule*, *5* (2021), 5, pp. 1016-1023
[10] Singh, M., *et al*., Solid Oxide Fuel Cell: Decade of Progress, Future Perspectives and Challenges, *International Journal of Hydrogen Energy*, *46* (2021), 54, pp. 27643-27674
[11] Ferriday, T. B., *et al*., Alkaline Fuel Cell Technology A Review, *International Journal of Hydrogen Energy*, *46* (2021), 35, pp. 18489-18510
[12] Zhang, Y., *et al*.,Thermal-Expansion Offset for High-Performance Fuel Cell Cathodes, *Nature*, *591* (2021), 7849, pp. 246-251

[13] Fan, L., *et al*., Recent Development of Hydrogen and Fuel Cell Technologies: A Review, *Energy Reports*, *7* (2021), 2, pp. 8421-8446
[14] Cullen, D. A., *et al*., New Roads and Challenges for Fuel Cells in Heavy-Duty Transportation, *Nature Energy*, *6* (2021), 5, pp. 462-474
[15] Ahmadi, P., *et al*., Dynamic Simulation and Lifecycle Assessment of Hydrogen Fuel Cell Electric Vehicles Considering Various Hydrogen Production Methods, *International Journal of Hydrogen Energy*, *47* (2022), 62, pp. 26758-26769
[16] Ghenai, C., *et al*., Technico-Economic Analysis of off Grid Solar PV/Fuel Cell Energy System for Residential Community in Desert Region, *International Journal of Hydrogen Energy*, *45* (2020), 20, pp. 11460-11470
[17] Okundamiya, M. S., Size Optimization of a Hybrid Photovoltaic/Fuel Cell Grid Connected Power System Including Hydrogen Storage, *International Journal of Hydrogen Energy*, *46* (2021), 59, pp. 30539-30546
[18] Kamel, A. A., *et al.*, Enhancing the Operation of Fuel Cell-Photovoltaic-Battery-Supercapacitor Renewable System through a Hybrid Energy Management Strategy, *International Journal of Hydrogen Energy*, *46* (2021), 8, pp. 6061-6075
[19] Salameh, T., *et al.*, Integrated Standalone Hybrid Solar PV, Fuel Cell and Diesel Generator Power System for Battery or Supercapacitor Storage Systems in Khorfakkan, United Arab Emirates, *International Journal of Hydrogen Energy*, *46* (2021), 8, pp. 6014-6027
[20] Samy, M. M., *et al.*, Optimal Economic Study of Hybrid PV-Wind-Fuel Cell System Integrated to Unreliable Electric Utility Using Hybrid Search Optimization Technique, *International Journal of Hydrogen Energy*, *46* (2021), 20, pp. 11217-11231
[21] Ferahtia, S., *et al.*, A Hybrid Power System Based on Fuel Cell, Photovoltaic Source and Supercapacitor, *SN Applied Sciences*, *2* (2020), 5, pp. 1-11
[22] Inci, M., *et al.*, A Modified Energy Management Scheme to Support Phase Balancing in Grid Interfaced Photovoltaic/Fuel Cell System, *Ain Shams Engineering Journal*, *12* (2021), 3, pp. 2809-2822
[23] Bo, G., *et al.*, Optimum Structure of a Combined Wind/Photovoltaic/Fuel Cell-Based on Amended Dragon Fly Optimization Algorithm: A Case Study, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *44* (2022), 3, pp. 7109-7131
[24] Benlahbib, B., *et al.*, Experimental Investigation of Power Management and Control of a PV/Wind/Fuel Cell/Battery Hybrid Energy System Microgrid, *International Journal of Hydrogen Energy*, *45* (2020), 53, pp. 29110-29122
[25] Haddad, A., *et al.*, Triple Hybrid System Coupling Fuel Cell with Wind Turbine and Thermal Solar System, *International Journal of Hydrogen Energy*, *45* (2020), 20, pp. 11484-11491

Paper submitted: June 26, 2022
Paper revised: August 22, 2022
Paper accepted: August 31, 2022