Energy Management for SOFC Hybrid DC Microgrids When External Power Goes Up

Lin Zhang[1], Quanmin Niu[1], Yu Deng[1], Feng Wang[1], Chao Xie[1], Jinjing Wang[1],
Jian Zhang[2], and Hongtu Xie[2](✉)

[1] Department of Early Warning Technology, Air Force Early Warning Academy,
Wuhan 430019, China
[2] School of Electronics and Communication Engineering,
Shenzhen Campus of Sun Yat-sen University, Shenzhen 518107, China
`xiehongtu@mail.sysu.edu.cn`

Abstract. In the solid oxide fuel cell (SOFC) hybrid direct-current (DC) microgrids, the energy management for the high efficiency, fast power transients and thermal safety are the main difficult task for considering. In this article, the composition of the SOFC hybrid DC microgrids including the SOFC, lithium battery and supercapacitor is established, and then its stable operating requirement is discussed. Moreover, the control and optimization strategies, including the energy management techniques are designed for the SOFC, battery and supercapacitor to remedy the defects of the slow SOFC power transients. Among the energy management techniques, the control scheme based on the SOFC system optimal operating points (OOPs) is established to realize highest efficiency and static thermo-safety. Moreover, the voltage and current control strategy based on the proportional plus integral (PI) controller is set up to maintain load terminal voltage to 220 V. In the end, the experimental results are shown to verify the effectiveness of the proposed control strategies. In addition, the SOFC/battery/supercapacitor-based DC microgrids shows the comparative advantage in the fast load tracing.

Keywords: Solid oxide fuel cell · Energy management techniques · Direct-current microgrids · High efficiency · Fast power transients · Thermal safety

---

This work is supported by the Guangdong Basic and Applied Basic Research Foundation (Grants No. 2021A1515010768 and No. 2023A1515011588), the Shenzhen Science and Technology Program (Grant No. 202206193000001, 20220815171723002), the National Natural Science Foundation of China (Grants No. 62203465, No. 62001523, No. 62201614 and No. 6210593), the Science and Technology on Near-Surface Detection Laboratory Pre-Research Foundation (Grant No. 6142414200607), the Science and Technology Talents Foundation of Air Force Early Warning Academy (Grant No. 2021KJY11), and the Fundamental Research Funds for the Central Universities, Sun Yat-sen University (Grant No. 23lgpy45.)

Lin Zhang and Hongtu Xie are the co-first authors, who share the first authorship and have contributed equally to this work.

H. Yang et al. (Eds.): SmartGIFT 2022, LNICST 483, pp. 284–294, 2023.
https://doi.org/10.1007/978-3-031-31733-0_24

1 Introduction

The microgrid is one of the fastest growing smart power systems, which plays an important role in the incremental electric power consumption [1–3]. Among the microgrids, the direct-current (DC) microgrids pay the more attention due to the advantages of the efficiency, reliability, high power quality, reduced power loss, improving transactive energy and the elimination of frequency and phase control [4, 5]. The distributed generations can be selected as the fuel cells (FCs), battery, supercapacitor, wind and solar photovoltaics (PV) [2, 3].

Among the several novel propositions, the SOFC are one of the most popular and efficient FCs-based DC microgrids. In especial, it can generate the electricity directly from the electrochemical reaction with the least spread of the pollution compared to the conventional energy production methods [6]. However, as the SOFC operates in the medium-high temperature, the poor thermal response must be given priority to consider. What's more, the lack of the external load following and system efficiency should also be addressed [7, 8]. To solve these issues and many others, our group and other teams have done a lot of works.

Currently and in the future, thermal safety control in the SOFC-based DC microgrids is critical. Our previous works have studied the operational safety by considering the temperature constraints in SOFC system. Some researches design the system controller to provide excess air to cool the SOFC stack [9–11], including a PI controller, a multivariable controller and so on. All the above controllers are suitable for SOFC system overheat control. Another point to consider is getting high efficiency output in FCs-based DC microgrids, our and other groups have many groundbreaking researches on it. Especially, the optimal operation points (OOPs) and the corresponding optimize external load power switch schemes have been discussed to obtain the maximum output efficiency [12–15]. Huang has studied the impact of the fuel utilization (FU) on the net efficiency of SOFC stand-alone system [12]. Zhu has proposed a novel combined cooling, heating and power (CCHP) system. The system has a high electrical efficiency of 52% and overall efficiency of 75%. Based on above, the parameter study and multiple objective optimization are conducted to get higher output efficiency [13]. Zhu also has optimized the system efficiency by controlling the SOFC fuel utilization through the parametric analysis [14]. Tan assesses the integrated energy efficiency ratio and CO_2 emission trend to obtain a much higher primary energy efficiency [15]. However, all the maximum efficiency obtained in the SOFC system at the intersection of the safety constraints. Few scholars research related the topics that ensure process safety and simultaneously optimizes the energy-efficiency.

The rapid load following is another key point in system control objective of SOFC-based DC microgrids. Plenty of the control schemes have been presented and investigated to maintain quick power following. Kandepu has developed a control architecture at the cost of the output efficiency for a SOFC-GT-based independent station [16]. Wang has proposed a novel operating method by combining the multi-controlled circuits with the protective circuits to achieve the rapid external load tracing and safety reliability and maintain-ability in SOFC system [17]. However, the quick-speed load following on the basis of optimal efficiency and thermal safety in static operating conditions should be focused on in this paper.

The main purpose of this article is to design the energy management scheme of the SOFC hybrid DC microgrids considering the system efficiency, fast power transients and thermal safety. This paper is organized as followings. Section 2 presents a SOFC hybrid DC microgrid architecture, containing stand-alone SOFC, lithium battery and supercapacitor, and then deals with its essential operational requirements. Section 3 presents the energy management and control strategies of the SOFC hybrid DC microgrids. The article finally gives the conclusion in Sect. 4.

2 SOFC Hybrid DC Microgrid System Architecture

The overall structure and distribution of the SOFC hybrid DC microgrids system is shown in Fig. 1. It mainly consists of the SOFC independent station, the lithium battery, the super capacitor, the DC/DC boost converters, the DC microgrids network and DC load. The battery and supercapacitor are preferred with the combinations because of the SOFC cannot reimburse for the fast load following [18, 19], and the required transient power is supplied to the DC bus by the battery and supercapacitor. The DC/DC boost converters are provided to maintain the quick-speed external load requirements and system reliability improving [20].

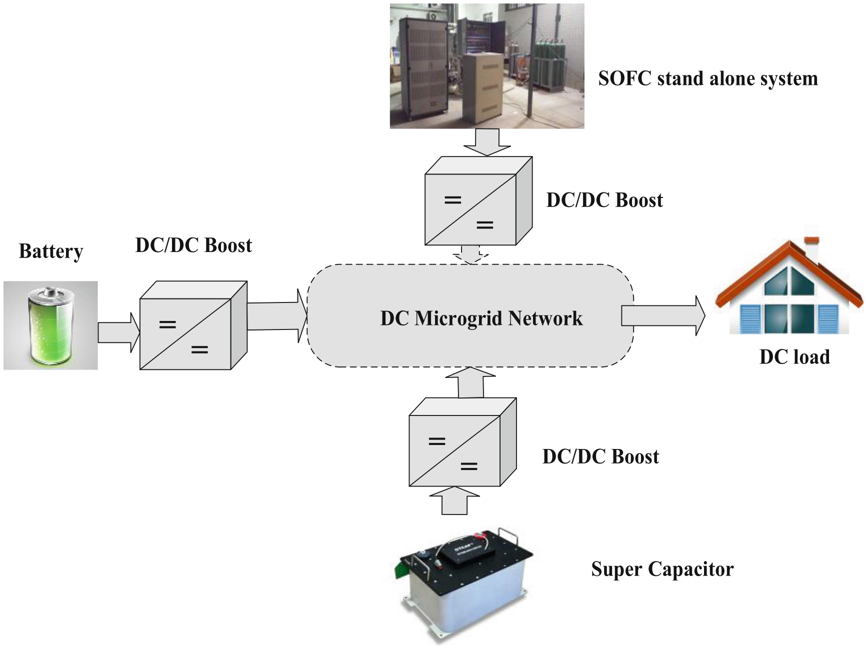

Fig. 1. Schematic diagram of the SOFC hybrid DC microgrids.

The systematic architecture of the SOFC is shown in Fig. 2. It mainly consists of two modules: the balance of plant (BOP) and SOFC stack. BOP plays an auxiliary role in SOFC system generation, it mainly consists the gas feed pipes and valves, the secondary heat exchangers, the tail gas recovery unit (burner). The stack operating power range is about 1 kW to 6 kW in different working conditions. The SOFC electrical output energy is provided by gas electrochemical reaction directly in stack. The main function of secondary heat exchangers is to reduce the stack cathode and anode inlet temperature difference. The heat source inlet heat exchangers are derived from burner. The main role of burner is to increase fuel utilization by making the exhaust gas burn completely. Meanwhile, an extra-second air bypass manifold is added to SOFC system to prevent excessive temperature in stack.

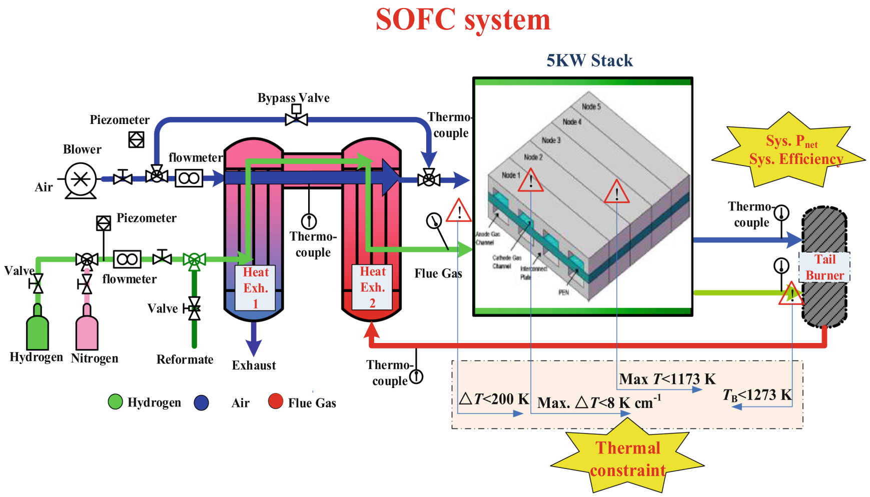

Fig. 2. Overall SOFC stand-alone system layout.

Our early works have studied the SOFC system structure, the simulation stratagem, the parameter and system-level optimization and the control strategies [21–24]. The battery of Li_ion is considered in our paper as it has been proving of the good energy density and electrical efficiency compared to other energy modes. Supercapacitor is known as the Electric Double Layer Capacitors (EDLCs), which can charge and discharge the more electrical energy because of its high capacitance. Their simulation process can be referred to [25].

Moreover, the interrelating parameter of Li_battery and supercapacitor models are listed in Table 1.

Table 1. Input parameters of the battery and supercapacitor models

Battery		Supercapacitor	
Nominal voltage (V)	28	Rated capacitance (F)	15.6
Rated capacity (Ah)	6.6	Equivalent series resistance DC (Ω)	2.1e−3
Maximum capacity (Ah)	40	Rated voltage (V)	16
Fully charged voltage (V)	32.42	Surge voltage (V)	18
Nominal discharge current (A)	17.4	Number of series capacitor	6
Internal resistance (Ω)	0.012	Number of parallel capacitor	1
Capacity (Ah)@Nominal voltage	36.17	Number of layer*	6
Initial state-of-charge (%)	90	Molecular radius (m)*	4e−10
Battery voltage response time (s)	30	Operating temperature (°C)	25

2.1 Thermal Performance Indices

The high system temperature or temperature gradient in the SOFC hybrid DC microgrids may lead system material deforming even unrepairable failure. This paper mainly considers four temperature constraints in the following.

(1) Burner temperature $T_B \leq 1273$ K.
(2) Maximum positive electrolyte-negative (PEN) temperature Max. $T_{PEN} \in [873\,\text{K},\ 1173\,\text{K}]$.
(3) Maximum PEN temperature gradient Max. $|\Delta T_{PEN}| \leq 8\,\text{Kcm}^{-1}$.
(4) Stack inlet temperature difference $\Delta T_{inlet} \leq 200\,\text{K}$.

2.2 System Efficiency Indices

In addition to the thermal safety, the system efficiency indices mainly include the operating parameters. The combined operation parameters, including the system inlet air flow rate (F_{air}), fuel flow rate (F_{H2}), system current (I_S), and bypass valve opening ratio (BP), are selected as assemble regulating variables in our paper. The range of their values are in the following.

(1) Inlet air flow rate $F_{air} > 0$;
(2) Inlet fuel flow rate $F_{H2} > 0$;
(3) SOFC system current $I_S \in [10\,\text{A},\ 70\,\text{A}]$.
(4) Bypass valve opening ratio $BP \in [0,\ 0.3]$.

Based on these performance indices, and comprehensive considering system thermoelectric synergy, as well as thermal safety and high efficiency. The optimal operating points (OOPs) are manipulated to achieve all the above operating requirements above. The OOPs under different operating power have been processed in the static state by the traversal optimization strategy in our previous studies in [21–24], as shown in Table 2.

Table 2. OOPs of the SOFC stand-alone system

P_{net} (W)	I_{s}(A)	F_{air} (mol/s)	F_{H2}(mol/s)	BP (%)
1000	10	0.09920	0.00772	0.2
2000	20	0.19841	0.01543	0.1
3000	32	0.34390	0.02469	0
4000	44	0.43649	0.03419	0
5000	52	0.57538	0.04774	0

3 Energy Management and Control Strategies

The response time of the SOFC-based DC/DC microgrid output power is within tens of second, which is insatiable for the rapid external load following. Especially in the scenarios of external load power rising. In this section, the SOFC hybrid DC microgrids are analyzed to highlight the load power rising transients.

The control and energy management strategies for the SOFC hybrid DC microgrid is shown in Fig. 3(a), for the purpose of the fast load following, thermal management and high efficiency. The DC demanded voltage is controlled by the voltage and current regulator (Fig. 3(b)) though their associated boost converters. The DC/DC converter can allow the voltage conversion as well as the full control of the fuel cell current and DC bus voltage. The average value of the DC/DC converter models can be referred to [26] for this study. The optimal regulator mainly control the load demanded power by referring to the OOPs. What's more, as three sources of the energy is introduced here, the energy management strategies (Fig. 3(c)) should be analyzed to highlight the fast load following.

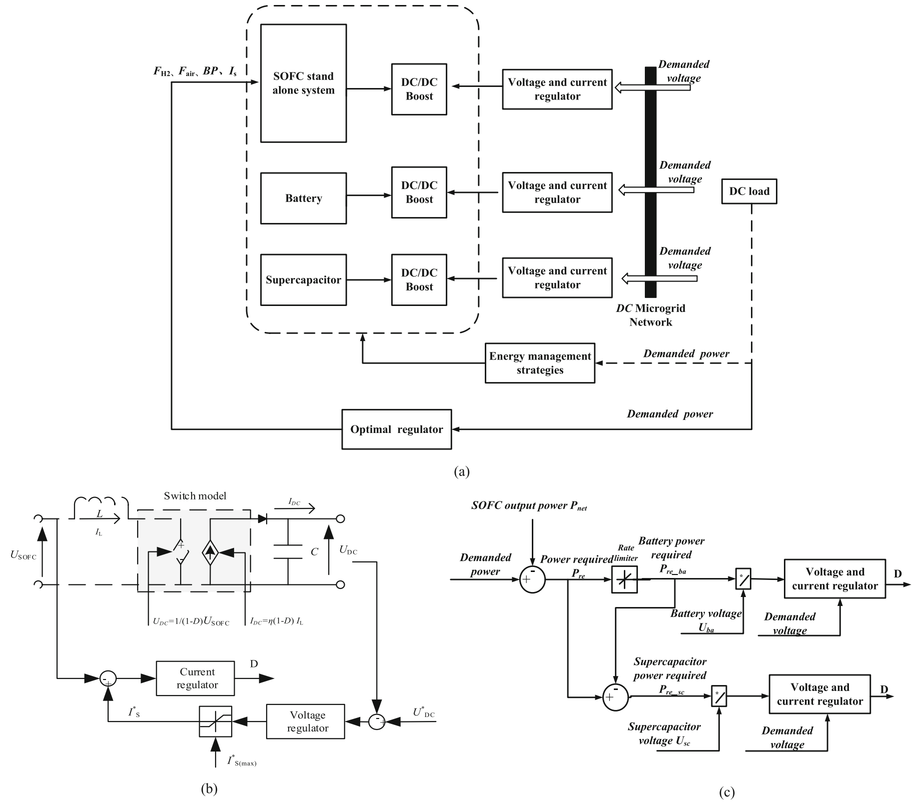

Fig. 3. Control and energy management strategies. (a) The overall control layout; (b) Boost type DC/DC converter model; (c) Energy management strategies.

As shown in Fig. 3(c), the system energy management strategies are designed based on SOFC system net output power (P_{net}) and the load demanded power. Their difference is the power required during the external load power step up. The battery and supercapacitor mainly provide the required energy. The required battery power is adopted by the power slope limitation, then the residual required power can be provided by the supercapacitor. Then, their input current of the DC/DC boost converter can be obtained from their required energy and voltage.

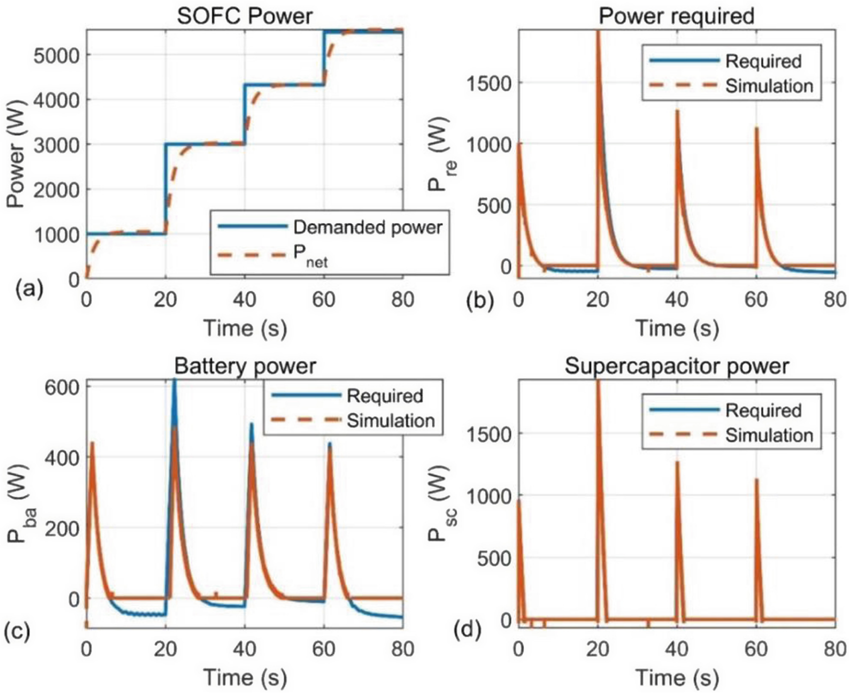

Fig. 4. Power results for the energy management strategies.

The power results of the above introduced control scheme is demonstrated as Fig. 4. The simulation results show the favorable power provided to the DC microgrid to remedy the defects of the slow SOFC power transients (Fig. 4(a)), and they all show the high accuracy according to the calculated required power (Fig. 4(b)–Fig. 4(d)).

Performance of the related electrical results in the SOFC hybrid DC microgrids is observed in Fig. 5. The electrical output characteristics (i.e. the voltage, current, SOC and system efficiency) of the supercapacitor and SOFC independent power generation system all changes with the external load demand (Fig. 5(a)–Fig. 5(c)). Especially, the SOFC system is operated near highest efficiency by the introduced optimal control method based on OOPs. Figure 5(d) shows the DC microgrid voltage is well controlled to 220 V. Moreover, the response time of the load power in the SOFC hybrid DC microgrid is within seconds, which shows the superiority in comparison with the SOFC-based DC microgrid.

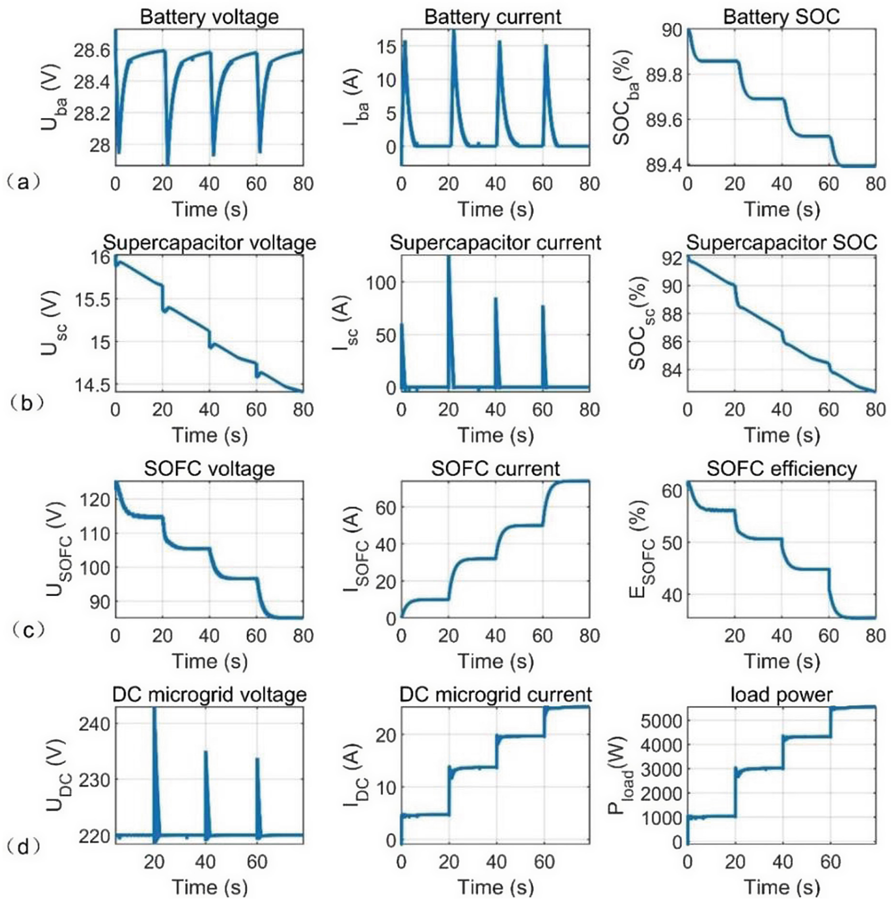

Fig. 5. Related electrical results in the SOFC hybrid DC microgrids. (a) Battery; (b) Supercapacitor; (c) SOFC; (d) DC microgrid load.

4 Conclusion

This paper presented the energy management strategies for the SOFC hybrid DC microgrids from the perspective of the high output efficiency, thermal safety and rapid load tracing response. The architecture of the SOFC hybrid DC microgrids including the SOFC, lithium battery and supercapacitor is first introduced. Then, the system essential operational requirements, including the thermal performance indices, system efficiency indices and the OOPs are introduced and discussed. Considering the high system efficiency, static thermal safety constraints and rapid external load following, the control and energy management strategies to highlight the fast load following for the SOFC hybrid DC microgrid is introduced. As expected, the favorable power response time is achieved with in seconds, as the battery and supercapacitor can remedy the defects of the slow SOFC power transients. To conclude, the SOFC hybrid DC microgrid has a great superiority in the fast load tracing, especially when the external power step up. An alternative is to design the multi-objective optimization energy management strategies to optimize all the performance criteria in the SOFC hybrid DC microgrid, which is the next topic in our further studies.

References

1. Xu, L., Ibragimova, A., Shilova, K.: Analysis of international practice in the use of renewable energy sources (RES). In: IOP Conference Series: Earth and Environmental Science, pp. 0121880–1–0121880–6. IOP Publishing Ltd., Moscow (2022)
2. Deng, Y., Zhang, Y., Luo, F., Mu, Y.: Operational planning of centralized charging stations utilizing second-life battery energy storage systems. IEEE Trans. Sustain. Energy **12**(1), 387–399 (2021)
3. Zhang, Y., Xu, Y., Yang, H., Dong, Z., Zhang, R.: Optimal whole-life-cycle planning of battery energy storage for multi-functional services in power systems. IEEE Trans. Sustain. Energy **11**(4), 2077–2086 (2020)
4. Eid, A.: Utility integration of PV-wind-fuel cell hybrid distributed generation systems under variable load demands. Int. J. Electr. Power Energy Syst. **62**(11), 689–699 (2014)
5. Srinivasan, M., Kwasinski, A.: Control analysis of parallel DC-DC converters in a DC microgrid with constant power loads. Int. J. Electr. Power Energy Syst. **122**(4), 1–9 (2020)
6. Wang, Y., Li, S., Sun, H., Huang, C.: The utilization of adaptive African vulture optimizer for optimal parameter identification of SOFC. Energy Rep. **8**, 551–560 (2022)
7. Mumtaz, S., Khan, L., Ahmed, S., Badar, R.: Indirect adaptive soft computing based wavlet-embedded control paradigms for WT/PV/SOFC in a grid/charging station conneced hybrid power system. PLoS ONE **13**(4), 1–17 (2018)
8. Pranita, R., Sanjoy, K., Sujit, K.: Renewable energy generation system connected to micro grid and analysis of energy management: a critical review. Int. J. Power Electron. Drive Syst. **13**(1), 470–479 (2022)
9. Sorrentino, M., Pianese, C., Guezennec, Y.: A hierarchical modeling approach to the simulation and control of planar solid oxide fuel cells. J. Power Sources **180**(1), 380–392 (2008)
10. Huo, H., Wu, Y., Liu, Y., Gan, S., Kuang, X.: Control-oriented nonlinear modeling and temperature control for solid oxide fuel cell. J. Fuel Cell Sci. Technol. **7**(4), 0410051–0410059 (2010)
11. Hajimolana, S., Tonekabonimoghadam, S., Hussain, M., Chakrabarti, M., Jayakumar, N., Hashim, M.: Thermal stress management of a solid oxide fuel cell using neural network predictive control. Energy **62**(1), 320–329 (2013)
12. Huang, S., Yang, C., Chen, H., Zhou, N., Tucker, D.: Coupling impacts of SOFC operating temperature and fuel utilization on system net efficiency in natural gas hybrid SOFC/GT system. Case Stud. Therm. Eng. **31**(101868), 1–12 (2022)
13. Zhu, P., et al.: Achieving high-efficiency conversion and poly-generation of cooling, heating, and power based on biomass-fueled SOFC hybrid system: performance assessment and multi-objective optimization. Energy Convers. Manag. **240**(114245), 1–18 (2021)
14. Zhu, P., et al.: High-efficiency conversion of natural gas fuel to power by an integrated system of SOFC, HCCI engine, and waste heat recovery: Thermodynamic and thermo-economic analyses. Fuel **275**(117883), 1–13 (2020)
15. Tan, L., Dong, X., Gong, Z., Wang, M.: Analysis on energy efficiency and CO_2 emission reduction of an SOFC-based energy system served public buildings with large interior zones. Energy **165**(B), 1106–1118 (2018)

16. Kandepu, R., Imsland, L., Foss, B., Stiller, C., Thorud, B., Bolland, O.: Modeling and control of a SOFC-GT-based autonomous power system. Energy **32**(4), 406–417 (2007)
17. Wang, X., Lv, X., Mi, X., Spataru, C., Weng, Y.: Coordinated control approach for load following operation of SOFC-GT hybrid system. Energy **248**(123548), 1–15 (2022)
18. Armghan, H., Yang, M., Wang, M., Ali, N., Armghan, A.: Nonlinear integral backstepping based control of a DC microgrid with renewable generation and energy storage systems. Int. J. Electr. Power Energy Syst. **117**, 105613 (2020)
19. Ahmed, O.A., Bleijs, J.A.M.: Power flow control methods for an ultra capacitor bidirectional converter in DC microgrids–a comparative study. Renew. Sustain. Energy Rev. **26**, 727–738 (2013)
20. Liu, Z., Zhao, J., Zou, Z.: Impedance modeling, dynamic analysis and damping enhancement for DC microgrid with multiple types of loads. Int. J. Electr. Power Energy Syst. **122**(106183), 1–12 (2020)
21. Zhang, L., Li, X., Jiang, J., Li, S., Yang, J., Li, J.: Dynamic modeling and analysis of a 5-kW solid oxide fuel cell system from the perspectives of cooperative control of thermal safety and high efficiency. Int. J. Hydrogen Energy **40**, 456–476 (2015)
22. Zhang, L., Jiang, J., Cheng, H., Deng, Z., Li, X.: Control strategy for power management, efficiency-optimization and operating-safety of a 5-kW solid oxide fuel cell system. Electrochim. Acta **177**(20), 237–249 (2015)
23. Zhang, L., et al.: An optimization and fast load-oriented control for current-based solid oxide fuel cell system. J. Solid State Electrochem. **22**(9), 2863–2877 (2018). https://doi.org/10.1007/s10008-018-3996-x
24. Zhang, L., Shi, S., Jiang, J., Li, X.: Current-based MPC for operating-safety analysis of a reduced-order solid oxide fuel cell system. Ionics **25**(4), 1759–1772 (2018). https://doi.org/10.1007/s11581-018-2654-8
25. Tremblay, O., Dessaint, L.-A., Dekkiche, A.-I.: A generic battery model for the dynamic simulation of hybrid electric vehicles. In: IEEE Vehicle Power and Propulsion Conference, Arlington, TX, USA, pp. 284–289. IEEE (2007)
26. Zakzouk, N.E., Khamis, A.K., Abdelsalam, A.K., Williams, B.W.: Continuous-input continuous-output current buck-boost DC/DC converters for renewable energy applications: modelling and performance assessment. Energies **12**(11), 1–27 (2019)