INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
I. GARIP et al., Vol.14, No.1, March, 2024

A Renewable Microgrid with Hydrogen for Residential Use: Fuzzy Logic for Multi-Objectives

ilhan GARIP *‡, Zainab Failh Allami **, Hassan Mohammed Abid ***, Bahira Abdulrazzaq Mohammed ****, Ahmed A. Ali *****, Zamen Latef Naser ******, M. Mahdi Abdulhasan *******

*+ Department of Electrical and Electronics Engineering, Nisantasi University, Istanbul, Turkey

** Al-Manara College for Medical Sciences/ (Maysan)/Iraq

*** Mechanical engineering department/ Mazaya university college/ Iraq

**** Department of Medical Engineering / Al-Hadi University College/ Baghdad,10011, Iraq

***** College of Petroleum Engineering, Al-Ayen University, Thi-Qar, Iraq

****** College of Computer/ National University of Science and Technology, Dhi Qar, Iraq

*******Department of Medical Laboratories Technology/ AL-Nisour University College/ Baghdad/ Iraq

(ilhangarip24@gmail.com, Zainab56125@gmail.com, hasanalibid@gmail.com , abdulrazzaq@hotmail.com , ahmedhlail2024@hotmail.com , latef546267@gmail.com , abdulhasan@gmail.com)

‡ Corresponding Author; ilhan GARIP, Department of Electrical and Electronics Engineering, Nisantasi University, Istanbul, Turkey

Received: 23.10.2023 Accepted: 25.11.2023

Abstract- Microgrids that utilize renewable energy sources (RES) need storage systems so that excess renewable electric power can be stored and used at other times when production is short. Renewable energy sources do not have a constant and continuous supply. The multi-component nature of hydrogen hybrid renewable microgrids (production and storage elements with varying characteristics and dynamics) necessitates the implementation of energy management systems (EMS). This is a control system that aims to optimize each element in order to achieve proper microgrid operation by working in synergy. The article proposes the use of a renewable microgrid with hydrogen for the following applications. Fuzzy logic controllers (FLCs) are used to implement a residential SGE. Microgrid performance is to be improved in terms of efficiency, operating costs, and lifetime of its elements by addressing a multi-objective problem. A power balance will be considered, as well as the performance and degradation of its components as well as the cost/benefits of transferring energy with the main grid. Based on heuristic models or techniques, traditional SGE provides better performance and lower economic benefits.

Keywords: Hydrogen systems, Fuzzy logic control, Microgrids, Multi-objective control, Energy management systems

1. Introduction

The European climate policies emphasize renewable energies and distributed generation models in a context where fossil fuel dependence must be reduced. The residential market, which has very uneven demand patterns, is also crucial to decarbonising the economy, which necessitates making use of energy storage systems in order to ensure environmental sustainability [1]. The hybridization of battery-based and hydrogen-based storage systems is thus a promising storage solution for renewable microgrids. The basic structure of hydrogen fuel cells, if produced, stored, and consumed in the same grid, is usually composed of an electrolyzer, a storage tank, and a fuel cell [2]. Generally, the use of direct current (DC) buses improves the performance of this type of microgrid, avoiding, for example, problems associated with reactive power. This is because DC buses are more efficient at transmitting power than alternating current (AC) buses, and they are also easier to maintain. Additionally, hydrogen fuel cells are more efficient than batteries, so they can store more energy for a longer time [3]. Battery storage systems are most effective in short- to medium-term hybrid energy storage systems, while hydrogen storage systems are best in the long term. Multi-stack fuel cell systems have greater durability and efficiency in the microgrid because of their structure. The energy management system (EMS) of the microgrid requires more complex control when more variables are added. A microgrid can be managed both technically (satisfying demand) and economically (saving energy) by an EMS, which provides the microgrid with more degrees of freedom [4]. The management of storage systems can be accomplished through the use of BMS based on heuristic techniques, hysteresis, or deterministic rules. Batteries are recharged using renewable energy in these cases. The double hysteresis band is another method of reducing degradation experienced by hydrogen systems during startup and shutdown. Model-based BMSs can also be used to solve complex multivariable optimization problems using predictive control applications, as well as linear multi-objective time-invariant techniques for optimizing energy distribution in the short term and reducing the complexity associated with non-linear problems [5]. The references consulted, however, do not guarantee control of the DC bus nor do they discuss how modular fuel cell systems should be used and managed. The Mandani-type fuzzy control technique has been successful from a practical point of view for decades when it comes to dealing with complex nonlinear control problems. The control problem can therefore be solved using easy-to-understand linguistic rules instead of an explicit model [6]. The rules can incorporate the knowledge of an expert in the control problem addressed. A number of fuzzy logic control (FLC) solutions are found in the literature for the problem proposed in this work, including an optimised FLC based on genetic and evolutionary algorithms, which reduces the main electricity grid's operating costs and storage system's operating hours by incorporating the variability of the main electricity grid's prices and the intermittency of renewable energy sources. A CLB can also regulate the voltage on the DC bus of microgrids by controlling the power converters on renewable generators and storage systems [7]. Hydrogen is one of the most sensitive and expensive elements, so control actions focus primarily on improving the efficiency of the entire cycle (production-storage-consumption). The SGEs can be found in CLBs that aim to optimize the efficiency of the fuel cell, or the storage system along with the costs of the main electricity grid in order to get the fuel cell running at its highest efficiency [8]. In this study, the main novelty is the use of an energy management system based on CLBs to manage a renewable microgrid hybridized with hydrogen, which is connected to the main grid, and integrates the entire hydrogen cycle, residential loads, and electric vehicle charging. A lead-acid battery storage system is also integrated to meet short- and medium-term demand, as well as to stabilize the voltage on the DC bus [9]. The local controllers of the renewable sources feeding power to the DC bus are then only concerned with the maximum power transfer, not with stabilizing the voltage at their output. The microgrid also integrates a multi-stack fuel cell (MSFC), specifically two of them [10]. In addition to being capable of solving complex modeling and control problems heuristically [11], fuzzy logic is also capable of solving complex modeling and control problems analytically [12]. In addition to medical diagnosis, stock market forecasting, and robotics control, fuzzy logic has been successfully applied to a variety of real-world problems. The system also excels at predicting and controlling complex dynamical systems compared to conventional rule-based systems. The Mamdani fuzzy inference system [13] is well-known in renewable energy systems for its ability to generate practical controllers without precise plant models by using linguistic (heuristic) rules. As linguistic rules can simplify controlling complex systems [14], linguistic rules have attracted great attention. Modeling complex non-linear systems with this system is advantageous, as well as dealing with uncertainty and imprecise information. It is also relatively inexpensive and easy to use, so it makes a good alternative to conventional energy sources. This type of fuzzy control system makes part-load operation of hydrogen-based systems such as fuel cells and electrolyzers possible. The reason for this is that this type of control system can adjust the production rate in response to demand and minimize energy loss during part-load operation [15]. The microgrid should become more efficient as part-load operation improves efficiency for all these devices. Microgrids can reduce energy consumption during periods when demand is low because they can adjust their production rates accordingly. The microgrid can thus utilize less energy overall, leading to greater energy efficiency [16]. The designed CLB, which implements the SGE, allows a safe operation of the microgrid depending on the stored energy, DC bus voltage, power balance, degradation and efficiency of the storage system, and the cost of interchange with the main grid, which enables the solution of a complex multi-objective problem. Furthermore, simulation results indicate that the microgrid performs better economically and technically.

2. Description of the microgrid under study

This microgrid consists of a 360 VDC bus, which is powered by a field of photovoltaic (PV) panels of 10 kWp power that are connected through a DC/DC converter to the DC bus via a DC/DC converter. For energy storage, there is a 36kWh lead acid battery bank available for short-medium term response and a hydrogen system consisting of a 1 Nm3/h alkaline electrolyser, 30bar hydrogen tank with a volumetric capacity of 1 Nm3 as well as a 6 kW PEM (polymer electrolyte membrane) fuel cell module system available for long term response. There are two stacks of fuel cells connected in parallel, each with a different degree of degradation [11]. The microgrid is also bidirectionally connected to the main power grid (Figure 1). In the microgrid, the power balance is determined by the difference between renewable energy generation and demand, which must either be met by the hybrid energy storage system (SHAE) or by the main electricity grid. In the power balance, a negative sign indicates power drawn from the bus, while a positive sign indicates power injected into the DC bus (1):

$$P_{BAL}[k] = P_{FV}[k] - P_{CARGA}[k] = P_{BAT}[k] + P_{H_2}[k] + P_{RED}[k] \quad \text{--------} \ (1)$$

Where:

$P_{FV}[k]$ – Power generated by the PV panels (W)
$P_{CARGA}[k]$ – Power demanded by the load (W)
$P_{BAT}[k]$ – Battery power (W)
$P_{H_2}[k]$ – Hydrogen system power (W)
$P_{RED}[k]$ – Main grid power (W)

$P_{H_2}[k] y P_{RED}[k]$ *can be expressed as* (2):

$$P_{H_2}[k] = \begin{pmatrix} P_{ELE}[k] & P_{H_2}[k] < 0 \\ P_{PCME}[k] & P_{H_2}[k] \geq 0 \end{pmatrix} \text{ --------- } (2)$$

$$P_{Grid}[k] = \begin{pmatrix} P_{RED_{SAL}}[k] & P_{RED}[k] < 0 \\ P_{RED_{EN}}[k] & P_{RED}[k] \geq 0 \end{pmatrix}$$

Where:

$P_{ELE}[k]$ – Power consumed per electrolyser (W)

$P_{PCME}[k]$ – Power generated by the PCM (W)

$P_{RED_{SAL}}[k]$ – Power fed into the main electricity grid (W)

$P_{RED_{EN}}[k]$ – Power supplied by the main electrical network (W)

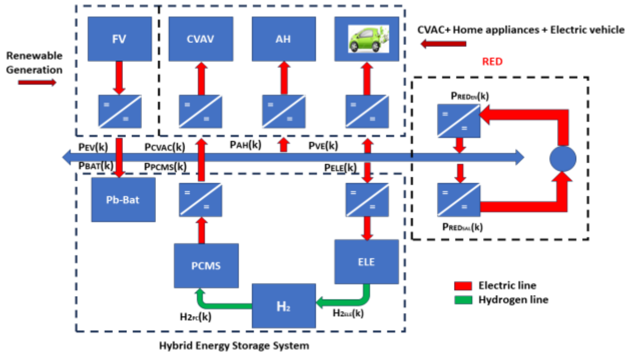


Fig 1. Architecture of the microgrid under study

3. Design of the SGE based on fuzzy logic

It is necessary to take local control actions to avoid high fuel degradations as a result of the short lifetime of the fuel cells, which are highly dependent on the operating conditions. The local control actions involve monitoring the fuel performance and adjusting the operating conditions as needed to ensure that the fuel cells are functioning optimally and the fuel degradation is minimized [12]. In addition, the hydrogen cycle has a low efficiency, which makes it necessary to consider the operating power, the operating time, and the number of cycles. A microgrid's power set point needs to be calculated based on its power balance, its stored energy, and its cost of connecting to the main grid from an economic perspective. This means that the hydrogen cycle needs to be optimized in terms of cost, efficiency, and reliability in order to be viable in a microgrid setting. Additionally, the cost of connecting to the grid needs to be taken into consideration when setting the microgrid's power set point [13].

3.1. Structure of the Fuzzy Logic Controller

Power balance is crucial to the operation of the SHAE and its interaction with the main power grid. Thus, we defined a SGE (Figure 2) based on two controllers: one for excess power moments (CLBE) and one for deficit power moments (CLBD), both of which operate simultaneously. The CLBE controller is responsible for absorbing excess power from the main power grid, while the CLBD controller is responsible for releasing stored energy from the main power grid. This balance ensures that the SHAE is always in equilibrium with the main power grid. The output variables of the CLB are also determined according to the sign of the power balance using a controller based on events (CBE). The CBE controller detects any changes in the power balance and adjusts the output variables accordingly to ensure that the SHAE is always in equilibrium with the main power grid [14]. This is done through an automatic process that determines the sign of the power balance and adjusts the output variables accordingly. Finally, a local CLB (CLBPCME) has been designed to calculate the operating power of each stack based on its accumulated degradation in order to extend the lifetime of the PCME. The local CLB continuously monitors the degradation of the stack and calculates the expected operating power based on the current degradation rate. This allows the PCME to adjust its operating power accordingly, resulting in an increased lifetime.

3.2. Fuzzy sets

Each fuzzy variable's universe of discourse has been defined based on the safe operating limits that ensure the microgrid's proper operation, as well as the manufacturer's specifications. According to Table 1, each of the fuzzy variables has a lower and upper limit.

Table 1: Operating range of fuzzy variables

Variable	Lower limit	Upper limit	Variable	Lower limit	Upper limit
$C_{VE}[k]$	0.02 €/kWh	0.09 €/kWh	$P_{BAL}[k+1]$	-15kW	15kW
$C_{cE}[k]$	0.02 €/kWh	0.13 €/kWh	$P_{PCME}[k+1]$	0kW	8kW
$D_{EST_{1,2}}[k]$	0 mV/cell	100 mV/cell	$EO_{EST_{1,2}}[k]$	0kW	4 kW
$NH[k]$	4Nm^3	28Nm^3	SOC [k]	40%	80%
$P_{BAL}[k]$	-15kW	15kW	$V_{BAT}[k]$	320V	430V

Where:

$C_{VE}[k]$ – selling price of energy to the grid (€/kWh)

$C_{cE}[k]$ –buying price of energy from the grid (€/kWh)

$D_{EST_{1,2}}[k]$ – degradation of each stack (mV/cell)

$NH(k)$- level of hydrogen stored in the tank (Nm3)

$EO_{EST_{1,2}}[k]$ - operating status of each stack (ON/OFF)

$SOC(k)$- battery charge status (%)

$V_{BAT}[k]$ – battery voltage (V)

A fuzzy rule base has been defined for each controller, based on the design of CLBE (situations of excess power in the microgrid), CLBD (situations of power deficit in the microgrid), and CLBPCME (control of the PCME stacks). The membership functions of each basis are trapezoidal and triangular, with a degree of membership in the interval [0,1]. The rule bases have been designed according to the mode of operation required for the SGE: when there is surplus renewable power in the microgrid (CLBE, Figure 3), it is first used to recharge the battery (this keeps the DC bus voltage stable), then it is balanced based on the price of selling energy to the main grid and the availability of hydrogen [13]. The first method is to use the energy stored in the batteries and then the hydrogen stored in the tank to ensure the power balance in a microgrid with a deficit of renewable power (CLBD, Figure 3).

3.3 The Framework of Fuzzy Logic Control (FLC)

Fuzzy logic control (FLC) is the most active research area in the application of fuzzy set theory, fuzzy reasoning, and fuzzy logic. The application of FLC extends from industrial process control to biomedical instrumentation and securities. Compared to conventional control techniques, FLC has been best utilized in complex ill-defined problems, which can be controlled by an efficient human operator without knowledge of their underlying dynamics. A control system is an arrangement of physical components designed to alter another physical system so that this system exhibits certain desired characteristics. There exist two types of control systems: open-loop and closed-loop control systems. In open-loop control systems, the input control action is independent of the physical system output. On the other hand, in a closed-loop control system, the input control action depends on the physical system output. Closed-Hoop control systems are also known as feedback control systems. The first step toward controlling any physical variable is to measure it. A sensor measures the controlled signal, A plant is a physical system under control. In a closed-loop control system, forcing signals of the system inputs are determined by the output responses of the system.

3.4 Encoding Methods for Membership Functions

In the fuzzy theory, fuzzy set A of universe X is defined by function µA(x) called the membership function of set A. We already discussed this point. µA(x): X → [0, 1], where µA(x) = 1 if x is totally in A; µA(x) = 0 if x is not in A; 0 < µA(x) < 1 if x is partly in A. This set allows a continuum of possible choices.

4. Result and Discussion

According to the data of the Institute for Energy Diversification and Saving (IDAE), the PV degeneration profile has been calculated based on the average value of the annual generation, and the demand profile on the typical consumption of a family. The power profile of Figure 2 shows the power profile of the different variables in Figure 1: renewable power (PFV), power for heating, ventilation, and air conditioning (PCVAC), and power for electric vehicle charging (PVE). In Figure 3, the first operating period (between hours 8 and 56) and the last operating period (between hours 18.93 and 18.97) were simulated for 792 days (the period in which the fuel cell system suffers the greatest degradation). Figure 4 compares the degradation of the two stacks that make up the PCME with the degradation they would have had if they applied other BMSs proposed in the literature to validate the behaviour of the developed BMS (BMS-CLB). It consists of two predictive models: SGE-MPC1, SGE-MPC2, and another based on hysteresis: SGE-HIST.

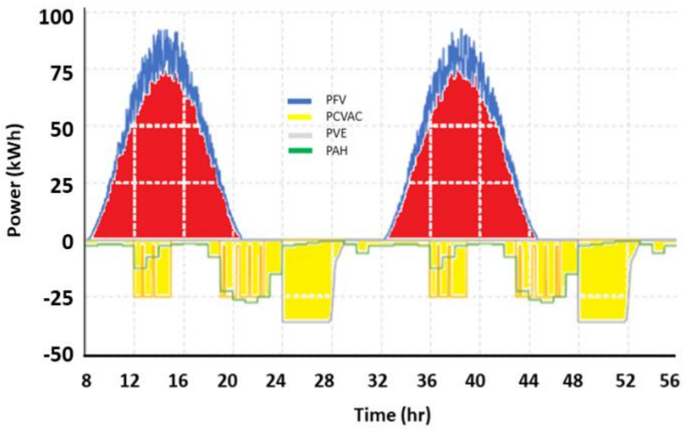
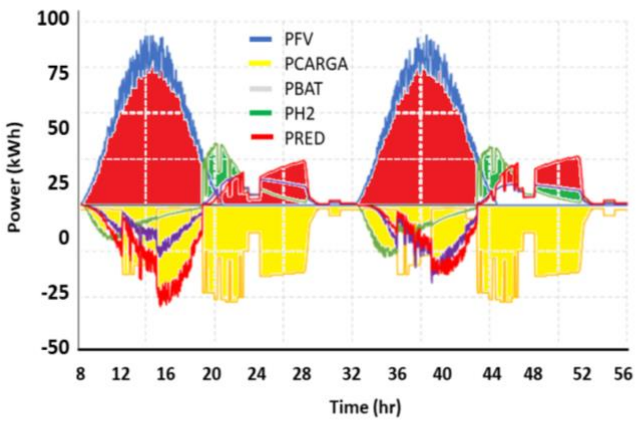
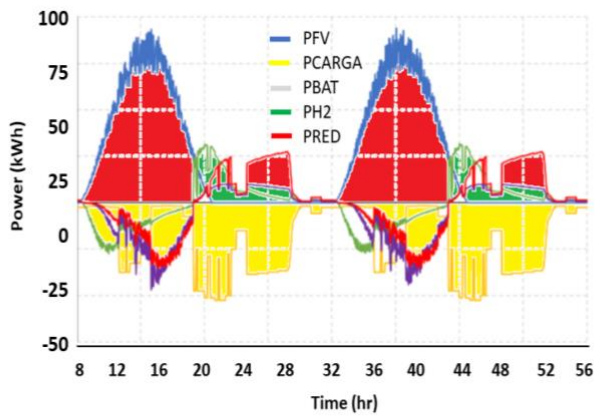


Fig 2. The power profile of the microgrid generation and consumption variables: PFV, PCVAC, PVE and PAH



[a]



[b]

Fig.3a & 3b. Microgrid power variables for the SGE developed during: a) first tranche (hours 8 to 56); b) last tranche (hours 18,920 to 18,968).

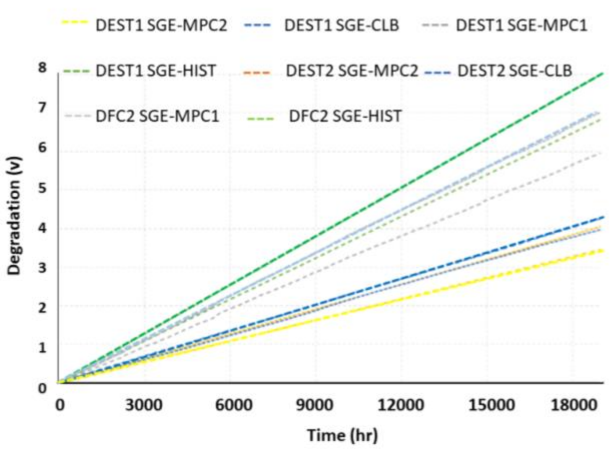


Fig 4. Degradation of each stack for different SGE: MPC-based (1 and 2), hysteresis-based (HIST) and the one developed in this work based on fuzzy logic (CLB)

Lastly, Figure 5 compares the cost obtained if the proposed BMS were used for the microgrid's operation with the cost obtained if the proposed BMS were one of the ones used for the microgrid's configuration in Figure 4. In the case of a connection with the main electric grid, the cost is greater than zero when the purchase of energy is made, and the cost is less than zero when the sale is made [15]. The microgrid is not connected to a permanent source of electricity, so there is no usual connection to the electricity grid.

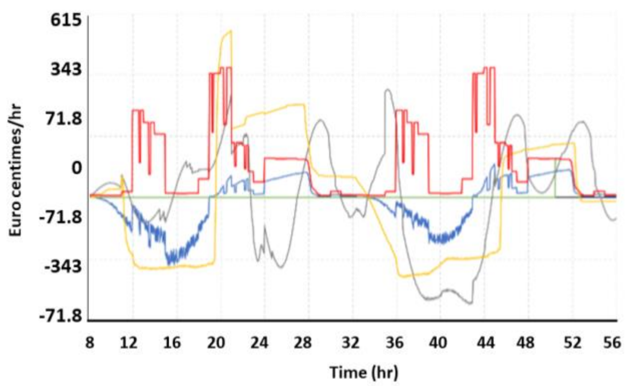


Fig 5. Operating cost of the microgrid for the BMS (LB), compared to the BMSs compared

As shown in Figure 3(a) and (b), the behavior of the microgrid varies between the first hours and the last hours of PCME operation, as the main grid will increasingly provide more and more power to meet demand as the accumulated degradation increases. During the first hours, the microgrid is able to provide a large percentage of the power demand, but as the degradation increases, the main grid will provide more and more power, and the microgrid's ability to provide power decreases [8]. Hydrogen will therefore be used less at the expense of a greater role for the main grid, which will result in higher costs. As the degradation increases, the microgrid's power output decreases, and the main grid's power output increases [1]. This means that more energy is needed from the grid, which in turn leads to higher costs. Alternatively, when it comes to the degradation of the PCME stacks (Figure 4), it can be seen that the CLB designed, by calculating the power distribution between stacks based on the accumulated degradation, achieves uniform degradation in both stacks. This is because the CLB takes into account the power distribution between stacks, which ensures that the degradation is evenly distributed between both stacks, leading to a uniform degradation in both stacks. Hysteresis-based SGEs (HISTs) and MPC1 prioritize the microgrid's own resources to make it independent of the main grid, causing greater degradation of the stacks in addition to being unbalanced [16]. This is because HISTs and MPCs prioritize the microgrid's own resources first, regardless of their cost, and this can cause the microgrid to be unbalanced, leading to higher energy costs and a greater degradation of the stacks. In MPC2, because it makes more conservative use of the SHAE, it limits the degradation of the stacks, achieving levels close to those achieved by the developed CLB; however, this degradation is not comparable. The CLB uses a larger SHAE, which allows it to generate more heat, which in turn causes more degradation of the stacks. MPC2, on the other hand, limits the SHAE size and so generates less heat, resulting in lower degradation of the stacks [13]. The proposed BMS developed in this work (CLB) has a significantly lower operating cost than all of the other BMSs analyzed, which is due to the fact that it is very little dependent on the main electricity grid. This is obviously much more evident if the usual situation of permanent connection to the main electricity grid is analysed, in which case the microgrid, with the BMS developed based on fuzzy logic, produces a savings (energy that would no longer be purchased from the main grid) of more than 3000 kWh, which means a savings of more than 3000 €. This is because the microgrid is able to respond quickly and efficiently to changes in demand, allowing it to use less energy from the main grid [9]. Additionally, the BMS can automatically adjust the system's parameters to optimize performance, resulting in further savings. Compared to the other SGEs considered, the authors' proposal saves more than 500 kWh compared to HIST, about 180 kWh compared to MPC1 and about 600 kWh compared to MPC2. This is because the authors' proposal uses more efficient algorithms and hardware components than the other SGEs considered. In terms of costs, except for the case of MPC1, which represents a cost of about -430 € (i.e. it represents benefits compared to the purchase and sale of electricity to the main grid), the CLB also generates higher economic savings, approximately 400 € versus HIST and more than 600 € versus MPC2. The authors' proposal requires fewer resources than the other SGEs, resulting in lower operational costs. Additionally, the proposal is more energy-efficient, which can lead to further cost savings.

5. Conclusion

This paper presents a BMS based on CLBs for residential microgrids powered by renewable energy sources. A multi-objective problem is being solved so that the performance of the microgrid can be improved from technical and economic perspectives. A multi-stack fuel cell controller uses two CLBs, as well as a local CLB to achieve this objective. This controller incorporates, at different levels, the knowledge of experts who are experts in the management of microgrids of the type presented here, in the form of fuzzy rules, which are intuitive and easy to understand. A comparison of the developed controller with other microgrid controllers in the literature reveals that the developed controller improves microgrid behavior. Fuel cell stack degradation is reduced to a uniform level in both stacks by the proposed BMS. As a result, it also achieves significant energy savings, which translate into substantial economic savings. It has been demonstrated that the BMS developed, in addition to being simpler to solve than other more complicated models and using an intuitive language, provides better results than other BMS proposals in the literature in terms of technical, economic, and even environmental aspects.

Acronyms

CLBC - Fuzzy Logic Control
CCCD - Continuous current
EMS - Energy management system
FER - Renewable Energy Sources
FLC - Fuzzy Logic Controller
MPC - Model Predictive Control
RES - Renewable energy sources
SG - Energy Management Systems
SHA - Hybrid Energy Storage System

Symbols

$\boldsymbol{CES}(\boldsymbol{k})$ - Power sale price to grid (€/kWh)
$\boldsymbol{CEP}(\boldsymbol{k})$ - Power purchase price to grid (€/kWh)
$\boldsymbol{DFC1,2}(\boldsymbol{k})$ - Fuel cell degradation (mV/cell)
$\boldsymbol{HL}(\boldsymbol{k})$Level of hydrogen stored in a tank (Nm^3)
$\boldsymbol{PBAT}(\boldsymbol{k})$ - Battery power (W)
$\boldsymbol{PELS}(\boldsymbol{k})$ - Power consumed by electrolyser (W)
$\boldsymbol{PGrid}(\boldsymbol{k})$ - Mains power (W)P('C0('(k)Mains power supplied by mains power (W)
$\boldsymbol{PGRIDOUT}(\boldsymbol{k})$ - Power fed into the main electricity grid (W)
$\boldsymbol{PH2}(\boldsymbol{k})$ - Hydrogen system power (W)
$\boldsymbol{PLOAD}(\boldsymbol{k})$Power demanded by the load (W)
$\boldsymbol{PMSFC}(\boldsymbol{k})$ - Power generated by the modular fuel cell system (W)
$\boldsymbol{PPV}(\boldsymbol{k})$ - Power generated by the PV panels (W)
$\boldsymbol{EOEST1,2}(\boldsymbol{k})$ - Operation status of each stack (ON/OFF).
$\boldsymbol{SOC}(\boldsymbol{k})$ - Battery state of charge (%)
$\boldsymbol{VBAT}(\boldsymbol{k})$ - Battery voltage (V)

References:

[1] F.K. Abo-Elyousr, J.M. Guerrero, and H. S. Ramadan, “Prospective hydrogen-based microgrid systems for optimal leverage via metaheuristic approaches,” Appl. Energy, vol.300, 117384, 2021.
[2] S.Al-Sakkaf, M.Kassas, M.Khalid, and M.A.Abido, “An Energy Management System for Residential Autonomous DC Microgrid Using Optimized Fuzzy Logic Controller Considering Economic Dispatch,” Energies, vol.12, 1457, 2019.
[3] V.A.Freire, L.V.R. de Arruda, C.Bordons, and J. J. Marquez, Optimal Demand Response Management of a Residential Microgrid using Model Predictive Control. IEEE Access, 2020.
[4] H. Merabet, T.Bahi, A.Boukadoum, and D. Drici, “Study and analysis of the operation of a Cuk converter for precise voltage regulation,” ijSmartGrid, vol 7, pp. 148-153, 2023.
[5] L.Amira, B.Tahar, and I.Yousra, “Performance of Meta-heuristic Algorithm for a Photovoltaic System under Partial Shade,” ijSmartGrid, vol. 7, pp. 160-167, 2023.
[6] F. J Vivas, A. De las Heras, F. Segura, and J. M. Andújar, “H_2RES_2 simulator A new solution for hydrogen hybridization with renewable energy sources-based systems,” Int. J. Hydrog. Energy, vol.42, pp.13510–13531, 2017.
[7] P.K.Polamarasetty, S.S.N.Ramakrishna, V.Muddala, and M. Vinay Kumar, “A Review on The Estimate Solar PV Cell Variables For Efficient Photovoltaic Systems,” ijSmartGrid, vol 7, pp. 154-159,2023.
[8] K. Ullah, G. Hafeez, I. Khan, S. Jan, and N. Javaid, “A multi-objective energy optimization in smart grid with high penetration of renewable energy sources,” Appl. Energy, vol.299, 117104, 2021.
[9] M. Kamruzzaman, Md. Anwarul, and Md. Anwarul Abedin, “Optimization of Solar Cells with Various Shaped Surficial Nanostructures,” ijSmartGrid, vol 7, pp.113-118, 2023.
[10] F.García-Torres, and C.Bordons, “Optimal Economical Schedule of Hydrogen-Based Microgrids With Hybrid Storage Using Model Predictive Control,” IEEE Trans. Ind. Electron., vol.62, pp.5195–5207, 2015.
[11] J.M.Andújar, J.M.Bravo, and A.Peregrín, “Stability analysis and synthesis of multivariable fuzzy systems using interval arithmetic,” Fuzzy Sets Syst. 148, 337–353, 2004.
[12] E.H.Mamdani, and S.Assilian, “An experiment in linguistic synthesis with a fuzzy logic controller,” Int. J. Man. Mach. Stud, vol.7, pp.01–13, 1975.
[13] A. Balodeau, and K. Agbossou, “Control analysis of renewable energy system with hydrogen storage for residential applications,” J. Power Sources, vol.162, pp.757–764, 2006.
[14] A.Harrag, and S.Messalti, “How fuzzy logic can improve PEM fuel cell MPPT performances? Int. J. Hydrog. Energy vol.43, pp.537–550, 2018.
[15] J.L.Casteleiro-Roca, A.J.Barragán, F.S.Manzano, J.L.Calvo-Rolle, and J.M.Andújar, “Fuel Cell Hybrid Model for Predicting Hydrogen Inflow through Energy Demand,” Electronics, vol. 8, pp.1325-34, 2019.
[16] I.Ngamroo, “Application of electrolyzer to alleviate power fluctuation in a stand-alone microgrid based on an optimal fuzzy PID control,” Int. J. Electr. Power Energy Syst. vol.43, pp.969–976, 2012.
[17] A.T. Sofyan, D.Nael, and A.M. Anas, “Detection of xylene as a detrimental chemical compound by employing a photonic crystal based on porous silicon,” ijSmartGrid, vol.7, pp.38-45, 2023.
[18] A. J. Calderón, F. J Vivas, F. Segura, and J. M, Andújar, “Integration of a Multi-Stack Fuel Cell System in Microgrids: A Solution Based on Model Predictive Control,” Energies, vol. 13, pp. 4924-4934, 2020.

[19] A. J. Barragan, J.M. Enrique, F. Segura, and J. M. Andujar, “Iterative fuzzy modeling of hydrogen Fuel Cells by the extended kalman filter,” IEEE Access, vol.8, pp.180280–180294, 2020.
[20] N.Nabipour, S.N. Qasem, and K.Jermsittiparsert, “Type-3 fuzzy voltage management in PV/Hydrogen fuel cell/battery hybrid systems,” Int. J. Hydrog. Energy, 45(56), 32478–32492, 2020.
[21] J.Hu, Y.Shan, J.M.Guerrero, A.Ioinovici, K.W.Chan, and J.Rodriguez, “Model predictive control of microgrids – An overview,” Renew. Sust. Energ. Rev., vol.136, 110422, 2021.
[22] J.V.Francisco, S.Francisca, M.A.José, P.Adriana, L.S.Jaime, I.Fernando, and L.Eduardo, “Multi-objective fuzzy logic-based energy management system for microgrids with battery and hydrogen energy storage system,” Electronics, vol.9, pp.01-23, 2020.