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Energy management based on a fuzzy controller of a photovoltaic/fuel cell/Li-ion battery/supercapacitor for unpredictable, fluctuating, high-dynamic three-phase AC load

Introduction. *Nowadays, environmental pollution becomes an urgent issue that undoubtedly influences the health of humans and other creatures living in the world. The growth of hydrogen energy increased 97.3 % and was forecast to remain the world's largest source of green energy. It can be seen that hydrogen is one of the essential elements in the energy structure as well as has great potential to be widely used in the 21st century.* ***Purpose.*** *This paper aims to propose an energy management strategy based a fuzzy logic control, which includes a hybrid renewable energy sources system dedicated to the power supply of a three-phase AC variable load (unpredictable high dynamic). Photovoltaic (PV), fuel cell (FC), Li-ion battery, and supercapacitor (SC) are the four sources that make up the renewable hybrid power system; all these sources are coupled in the DC-link bus. Unlike usual the SC was connected to the DC-link bus directly in this research work in order to ensure the dominant advantage which is a speedy response during load fast change and loads transient.* ***Novelty.*** *The power sources (PV/FC/Battery/SC) are coordinated based on their dynamics in order to keep the DC voltage around its reference. Among the main goals achieved by the fuzzy control strategy in this work are to reduce hydrogen consumption and increase battery lifetime.* ***Methods.*** *This is done by controlling the FC current and by state of charge (SOC) of the battery and SC. To verify the fuzzy control strategy, the simulation was carried out with the same system and compared with the management flowchart strategy. The results obtained confirmed that the hydrogen consumption decreased to 26.5 g and the SOC for the battery was around 62.2-65 and this proves the desired goal.* References 47, tables 7, figures 19.

Key words: **energy management strategy, fuzzy logic control, hybrid renewable energy source.**

Вступ. *В даний час забруднення навколишнього середовища стає актуальною проблемою, яка, безперечно, впливає на здоров'я людини та інших істот, які живуть у світі. Зростання водневої енергетики збільшилося на 97,3 %, і прогнозувалося, що вона залишиться найбільшим у світі джерелом зеленої енергії. Видно, що водень є одним із найважливіших елементів у структурі енергетики, а також має великий потенціал для широкого використання у 21 столітті.* ***Мета***. *У цій статті пропонується стратегія управління енергоспоживанням, заснована на нечіткому логічному управлінні, яка включає гібридну систему відновлюваних джерел енергії, призначену для живлення трифазного змінного навантаження змінного струму (непередбачувана висока динаміка). Фотоелектричні (PV), паливні елементи (FC), літій-іонні батареї та суперконденсатори (SC) – це чотири джерела, з яких складається відновлювана гібридна енергосистема; всі ці джерела підключені до шини постійного струму. На відміну від звичайних застосувань,ув цій дослідницькій роботі SC був підключений до шини постійного струму безпосередньо, щоб забезпечити домінуючу перевагу, що полягає в швидкому реагуванні при швидкій зміні навантаження та перехідних режимах навантаження.* ***Новизна***. *Джерела живлення (PV/FC/батареї/SC) координуються на основі їхньої динаміки, щоб підтримувати напругу постійного струму біля свого еталонного значення. Серед основних цілей, досягнутих стратегією нечіткого управління у цій роботі, - зниження споживання водню та збільшення терміну служби батареї.* ***Методи***. *Це робиться шляхом керування струмом FC та станом заряду (SOC) батареї та SC. Для перевірки стратегії нечіткого управління було проведено моделювання з тією самою системою та порівняння зі стратегією блок-схеми керування. Отримані результати підтвердили, що споживання водню знизилося до 26,5 г, а SOC для батареї становило близько 62,2-65, що доводить досягнення бажаної мети.* Бібл. 47, табл. 7, рис. 19.

Ключові слова: **стратегія енергоменеджменту, нечітке логічне управління, гібридне відновлюване джерело енергії.**

Introduction. The expansion of conventional power networks has led to the instability of the power network due to its inability to meet various energy requirements, especially in rural areas with difficult terrain and very low population density, where the decentralized supply of energy to remote areas has become necessary. The Renewable energy systems like a solar, wind, and hydrogen, to name a few, contribute effectively in global energy balance, These sources are sustainable and have zero emission compared to systems that rely on traditional fuels such heavy oil, natural gas, and coal [1], The system can reach optimal efficiency by combining these sources with energy storage elements [2, 3]. Although these resources are primarily weather-dependent, any significant changes in the weather can drastically affect power generation [4]. This hasn't stopped governments from increasing the percentage of renewable energy in their energy mix, which is predicted to reach 23 % by 2035 [5]. A hybrid power system (HPS) can alleviate the problem of energy demand, especially in distant places, when a self-contained renewable resource is unable to offer reliable and sufficient electricity. HPS is made up of a variety of non-renewable and renewable energy sources, as well as converters and energy storage system devices. It also has a number of advantages, including great flexibility and power management capabilities [6]. In [7] authors explained that hydrogen is the energy source of the future; he noted that the cost of hydrogen (CH) will decrease as its use grows and production and storage methods improve; he also discussed the necessity of producing hydrogen using electrical energy generated from renewable energy sources. Hydrogen energy has the biggest benefit over other sources of energy in that it can be stored and delivered. Solar energy, wind turbines, and hydroelectric power plants can all provide excess electricity that can be stored as hydrogen energy for later use. Energy can be continuously produced and stored in this manner. As a result, numerous researches have been conducted [8]. The polymer electrolyte membrane fuel cell (PEMFC) systems, according to [9], are one of the efficient energy conversion devices utilized for the direct conversion of hydrogen energy received from diverse RES into electrical energy. In [10] authors shows the impacts of lithium-ion batteries for renewable energy (wind and solar) storage for grid applications are assessed through a life cycle assessment covering the batteries supply phase, their end-of-life, and use. Results show that the new lithium-ion battery cathode chemistry has 41.7 % more particulate matter and 52.2 % more acidification.

Because of the growing demand for efficient, high-power energy storage, the development of supercapacitors (SCs) has gotten a lot of attention in recent years. Authors in [11] investigated how to improve the energy density of SCs for renewable energy generation applications. This potential was assessed by calculating the performance (energy and power) of a series of SCs that use advanced materials that electrochemists have been studying for the past 10-15 years. In [12] were considered that the SC is one of the greatest energy storage elements for hybrid electric power systems. Many studies have looked into HPS, which combine fuel cells (FCs) with batteries and SCs, In [13, 14] authors improved the energy management in hybrid FC/battery/SC for electric vehicle applications (FC as the primary source, and battery with the SCs as backup source). Authors provide a combination of artificial neural network and primary biliary cirrhosis in this article to control and manage the energy of this multisource system, the stability of the hybrid system while providing an acceptable solution for transferring energy between sources. In order to get greater dynamic performance, the system still need several advanced control approaches. Photovoltaic (PV) wind battery is another type of hybrid renewable energy systems used in energy systems to assess the charging and discharging capabilities of the system, for the energy management of this hybrid energy sources. In [15] displays an intelligent fractional order PID controller. Through a DC-link voltage, PV-wind-battery is connected to a smart grid. To extract the maximum power point (MPP) from the wind and PV, the converters are controlled by an intelligent fractional order PID method, despite the fact that this research gives predictions using the proposed technique while taking local uncertainty into account, the impact of climate conditions on the generated energy still standing. Authors in [16] present an optimized energy management strategy (EMS) for PV/FC/battery DC microgrid based on salp swarm algorithm (SSA), the proposed SSA-based EMS is evaluated and compared to the existing particle swarm optimization (PSO)-based EMS. The SSA provides a more stable working environment for the power system (FC and battery) than the PSO, because the planned EMS is dependent on a central controller, any failure of this controller could have significant implications for the power system, this can be avoided for decentralized control systems. Because of the advantages of using a SC during a load change that is transitory, surprising and quick. In [17] authors included the SC to the renewable hybrid power system (REHPS), which includes PV, PEMFC, battery, and SC. To achieve the maximum value of state of charge (SOC) and the lowest value of hydrogen consumption, the suggested energy management system employs a hybrid method that includes fuzzy logic, frequency decoupling, and state machine control strategies. The adaptive fractional fuzzy sliding mode control (AFFSMC) technique is provided for power management in a PV/FC/SC/battery hybrid system in grid-connected microgrid applications [18]. In operating settings, the AFFSMC outperforms the traditional PI controller, according to research. For the proposed system, a REHPS, a PV array serves as the major power source in this arrangement during day light when it is available and a FC (PEMFC) as a secondary power source during the night or in the shading time, battery and SC as storage elements and to provide transient load demand.

The goal of the paper is to try to improve some of the weaknesses and results of previous research, and that is by connecting the SC directly to DC voltage bus in order to ensure a speedy response during load fast change and load transient, also, in this work, hydrogen consumption and battery SOC were taken into account and optimized (for cost and lifetime cycle) in addition to combining all DC/DC converters into a single unit. This study describes energy management strategies for a fuzzy logic control approach for a REHPS (PV/FC/Battery/SC), The system's performance is simulated using the MATLAB/Simulink software, the results were compared to the control approach for management flowcharts, the system was also tested on a three-phase AC variable load, demonstrating its efficiency.

System description. REHPS investigated in this research is designed to provide power to a specific load, four sources make up the REHPS: a PV generator as a renewable energy source that serves as the primary source during daytime hours. The FC intervenes as a supplementary source at night or during shade period. When the load power is high, batteries serve as an energy storage element for the FC, ultracapacitors can be used as a transient power compensator or when changing loads quickly. To controlling the power of each source and maintaining a constant voltage level as much as feasible DC-DC converters regulate all energy sources and storage systems. Boost converter for PV and PEMFC power sources, as well as a bidirectional converter (buck and boost) to manage the charging and discharging of batteries, a three-phase DC-AC converter is used to provide the load with a three-phase regulated current source in this study. In order to expose the system's responsiveness under various scenarios, we assumed the load is a random variable load (Fig. 1).

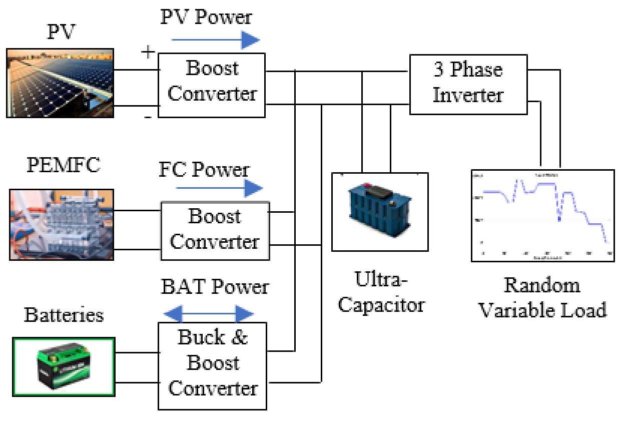


Fig. 1. Structure of the studied REHPS

The suggested energy management system uses the rule based fuzzy logics strategy. In Fig. 2 the hierarchical management and control system is illustrated as a block diagram with its inputs and outputs. The management method presented in this study is based on the following key criteria: lowest hydrogen use while maintaining maximum SOC, extended life cycle, and high overall system efficiency.

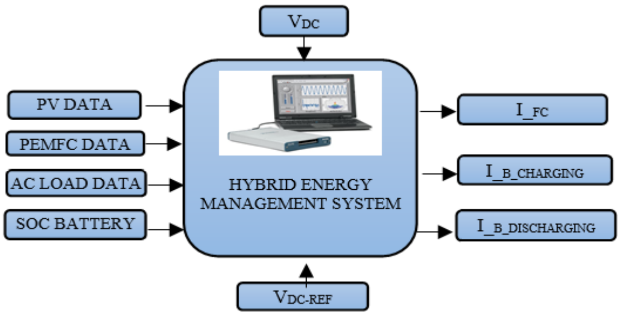


Fig. 2. Block diagram of the energy management system

Modeling and sizing of electrical system parameters.

1. PV source. A solar generator is made up of a group of basic PV cells that are linked in series and/or parallel to generate the necessary electrical characteristic, where their common model is depicted in Fig. 3.

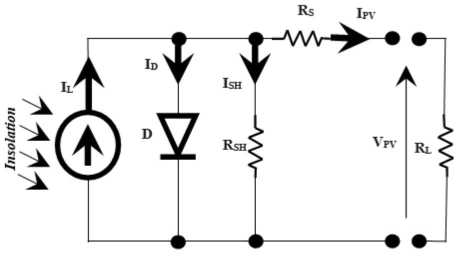


Fig 3. Single diode PV cell model

The photocurrent is I_{ph}, and the diode current is I_d. R_{sh} is connected to the non-ideal feature of the *p–n* junction and the presence of flaws along the cell's borders that favor a short-circuit path around the junction. R_S indicates the totality of the resistances confronted with the electrons' trajectory [19, 20].

The PV panel used in simulation in this work is referenced by: ASMS-180M from Aavid Solar Company (exists in MATLAB. According to our rated power (10 kW), we have used $M_s{\cdot}M_p$ = 6·10= 60 – PV panels to achieve this power value (Table 1).

Table 1

Simulation parameters of the used PV field

P_{MPP} – MPP power value, kW (180×6×10)	10.8
V_{MPP} – MPP voltage value, V (36×10)	360
I_{MPP} – MPP current value, A (5×6)	30
I_{SCS} – short circuit current value, A (5.5×6)	33
V_{0CS} – open circuit voltage value, V (45×12)	540

2. PEMFC generation system. PEMFC is a popular renewable energy source that has been recommended as preferred because to its benefits such as high efficiency (up to 45 %), high energy density (up to 2 W/cm^2), silent operation, low-temperature operation, quick start-up, and system resilience [21, 22]. It was frequently used for this purpose used in a number of applications for this reason, including vehicle propulsion, small-dispersed generation, and portable applications [23]. However, it has some disadvantages, including an inconsistent output voltage, a poor reaction to load fluctuations, and a high price [24]. Through electrochemical reactions of oxygen and hydrogen, PEMFC generates electricity-using hydrogen as a fuel, and because the PEMFC's only by-product is water, no emissions are produced. The FC's equivalent circuit is shown in Fig. 4 [25]. The parameters of the PEMFC used in simulation in this work are detailed in Table 2 (exists in MATLAB). DC/DC boost converter is attached to the PEMFC's output, the converter receives the reference FC current and uses it to adjust the amount of output power it sends to the system, the *I–V* curve for the FC employed in the proposed system is shown in Fig. 5 [26].

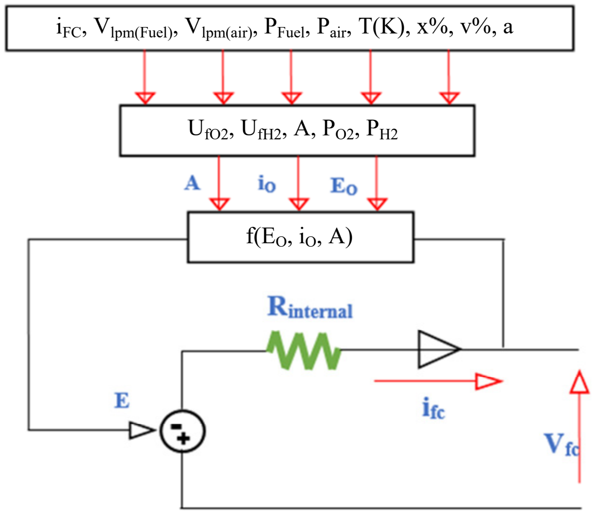


Fig. 4. FC equivalent circuit

Table 2

Parameters of the PEMFC data sheet

FC nominal parameters Stack Power Nominal	10287.5
FC nominal parameters Stack Power Maximal	12544
Nominal utilization hydrogen	98.98
Nominal utilization oxident	42.88
Nominal consumption fuel	113.2
Nominal consumption air	269.5
Temperature system, T	318

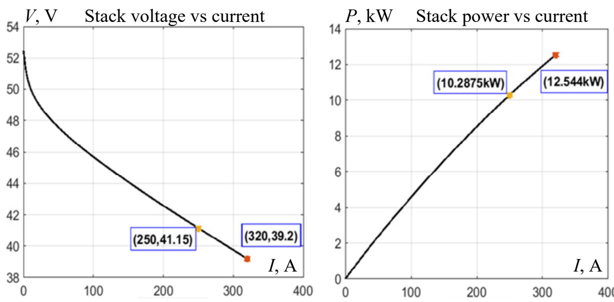


Fig. 5. The suggested system's *I–V* curve for the FC

3. Li-ion battery. Li-ion batteries were utilized for this research work, because, when compared to other battery types, they have shown to offer a high energy density and efficiency (such as lead-acid, NiCd or NiMH) [27], When considering lithium batteries, the SOC %, remaining usable life, and deterioration are the most significant characteristics to consider as well as various other factors such as detection of battery parameters, charge control, as well as battery protection and alarm [28, 29]. The updated model of the battery as a function of open cell ohmic resistance, cell circuit, cell inductance, capacitance, long/short time resistance, and the load current is represented by the equivalent battery circuit in Fig. 6.

Table 3 displays the battery parameters, to manage the battery's charging and discharging procedures, the battery's output is coupled to a buck/boost DC/DC converter.

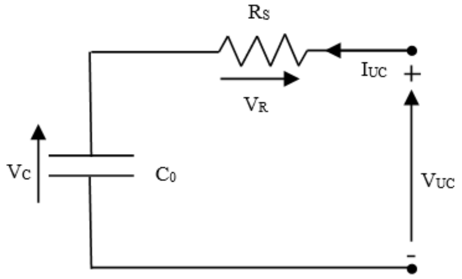


Fig. 6. Battery equivalent circuit

Table 3

Parameters of the Li-ion battery data sheet

Voltage nominal, V	48
Capacity rated, Ah	40
Initial SOC, %	65
Capacity maximum, Ah	40
Cut-off voltage, V	36
Voltage fully charged voltage, V	55.8714
Discharge current nominal, A	17.3913

4. Ultracapacitor. An ultracapacitor (UC), also known as an electrochemical double layer capacitor, is a type of capacitor that has a very high capacitance, is a low-voltage energy storage device that functions similarly to a battery but has a very high capacitance value. High power density, low series resistance, high efficiency, huge charge/discharge capacity, and reduced heating losses are all features of UCs [30]. These fast-response deep-discharge capacitors are suited for use across a broader temperature range. The terminal voltage of a UC, on the other hand, declines when the SOC diminishes, and the rate of reduction is dependent on the load current [31]. The basic UC model is given in Fig. 7.

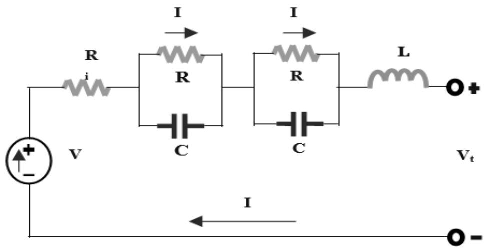


Fig. 7. Basic UC model

Table 4 shows the specifications of the UC that was employed.

Table 4

UC parameters

Capacitance rated, F	15.6
Equivalent DC series resistance, mΩ	150
Voltage rated voltage, V	291.6
Number of series capacitors	108
Number of parallel capacitors	1
Voltage initial, V	270

The energy management system is a computerized software that regulates the power response of each energy source in relation to load demand via the converters that are connected to it. The EMS has a significant impact on system overall performance and efficiency, fuel economy, and distributed generation service life, as well as managing the SOC and avoiding deep discharging, and maintaining DC voltage stability [32]. When discharging, the energy storage element was employed as a source of energy in this study, because the proposed system includes many electrical power sources such as PV and FC, an energy management approach was required to regulate, monitor, and enhance the system's operation in order to achieve the system's maximum performance [33, 34]. With REHPSs, a wide range of EMSs and control techniques are employed, In this research, the fuzzy logic control (FLC) was employed as a control strategy for calculating and setting the reference values of FC power, as well as the PI cascaded control for calculating and setting the reference values of battery charge and discharge currents.

Control of the active PV generator. The controller of the PV generator must manage PV voltage in order to adopt a maximum power point tracking (MPPT) approach in order to harvest the maximum power from the PV system. The PV generator's reference voltage is established using a basic perturbation and observation (P&O) based MPPT algorithm. The control unit from the duty cycle (u) to the PV voltage (V_{PV}) is shown in Fig. 8, two cascaded PI controllers complete this process, restoring V_{PV} to its reference [35, 36].

Table 5

Simulation parameters

PV converter	
Topology converter	Boost converter
Technic control	Two cascade PI controllers
Parameters control (kp, ki)	Voltage: (0,1131, 32) Current: (14,1421, 20000)

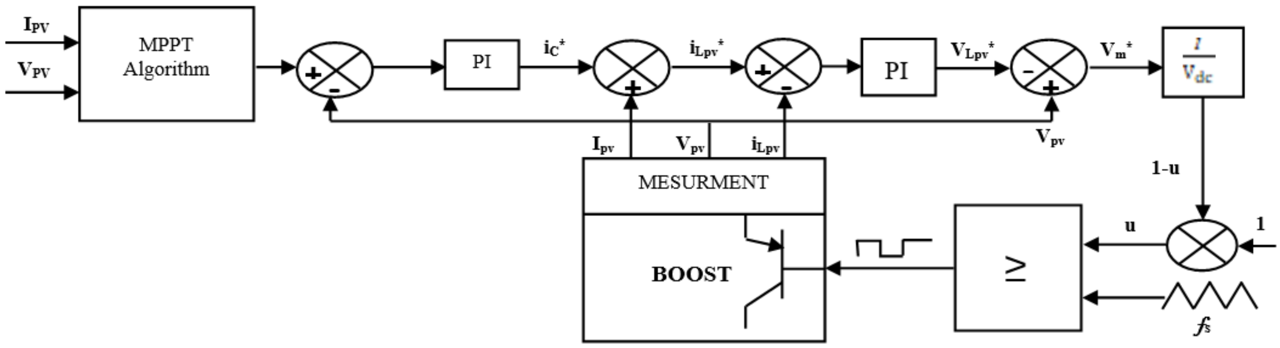


Fig. 8. CU from the duty cycle (u) to the voltage PV

Battery charging/discharging current control. For balancing power and regulating DC bus voltage, the battery pack is critical, the charging/discharging battery current is controlled in this study using a PI control method. It is determined by the difference between the DC voltage's real and reference values [37-41]. The PI control technique for the battery charge/discharge operation is shown in Fig. 9.

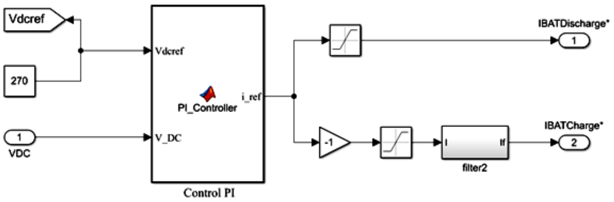


Fig. 9. Battery charge/discharge control approach based on PI

Fuzzy logic controller for PEMFC system. Instead of the usual true or false Boolean logic, the FLC is a control technique based on the level of truth (one or zero), fuzzification, fuzzy interface, and defuzzification are the basic control phases in fuzzy control [42-44]. The fuzzy IF/THEN rules are triggered to use the fuzzy interface for mapping the fuzzy values after the fuzzification technique changes the input values to fuzzy values, the defuzzification technique provides output values at the conclusion. As a control approach and in the application of systems optimization, fuzzy logic control is employed in hybrid power systems. The fuzzy logical control in this study contains two input variables and one output variable, where the input variables are excess demand power Δ_d and SOC, and the output variable is the FC system reference power Pfc_ref. The Δ_d is divided into four zones to provide this fuzzy control: very small (VS), small (S), medium (M), and big (B). Similarly, the battery SOC is divided into 3 categories: low (L), when SOC is less than SOC_{min}; good (G), when SOC is between 65 and 85; high (H), when SOC is greater than SOC_{max}. Pfc_ref, like Δ_d, is specified in 4 states, including VS, S, M, and B for the fuzzy output. Table 6 shows the rule foundation for the fuzzy logical control algorithm, which has 12 rules. Figures 10,*a–c* show the membership functions of the SOC, Δ_d, and Pfc_ref, respectively. The centroid method is used with Mamdani's fuzzy inference methodology for defuzzification.

The Pfc_ref is the output of the system control level in the PEMFC generating system. FC system reference output current Ifc_ref is then calculated by dividing the Pfc_ref by the FC voltage, through Fig. 11, the FC current reference value based on the reference power. Finally, the output current of the DC/DC converter is adjusted to this value by a current regulator [44-47]. Figure 12 depicts the control structure of the PEMFC generating DC/DC converter.

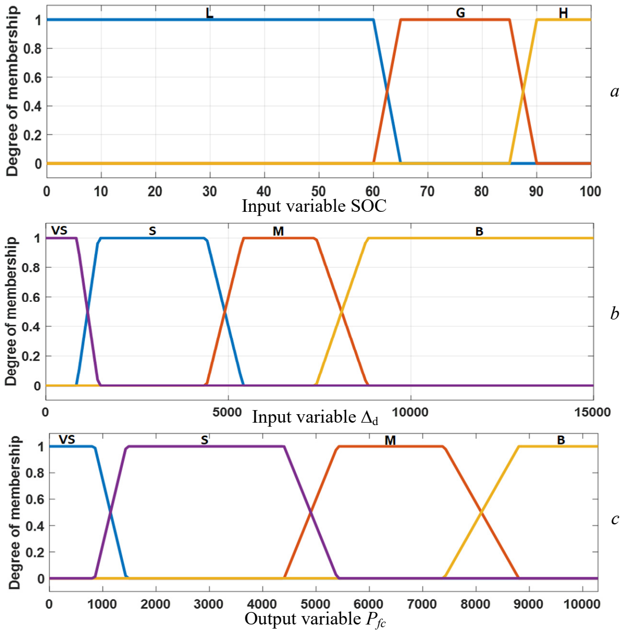


Fig. 10. *a* – battery SOC membership functions;
b – surplus demand power membership functions Δ_d;
c – FC power membership functions

Table 6

Fuzzy logical control's rule basis

FL rules			
1	If SOC is H	And Δ_d is VS	Then Pfc_ref is VS
2	If SOC is H	And Δ_d is S	Then Pfc_ref is S
3	If SOC is H	And Δ_d is M	Then Pfc_ref is M
4	If SOC is H	And Δ_d is B	Then Pfc_ref is B
5	If SOC is G	And Δ_d is VS	Then Pfc_ref is VS
6	If SOC is G	And Δ_d is S	Then Pfc_ref is S
7	If SOC is G	And Δ_d is M	Then Pfc_ref is M
8	If SOC is G	And Δ_d is B	Then Pfc_ref is B
9	If SOC is L	And Δ_d is VS	Then Pfc_ref is S
10	If SOC is L	And Δ_d is S	Then Pfc_ref is M
11	If SOC is L	And Δ_d is M	Then Pfc_ref is B
12	If SOC is L	And Δ_d is B	Then Pfc_ref is B

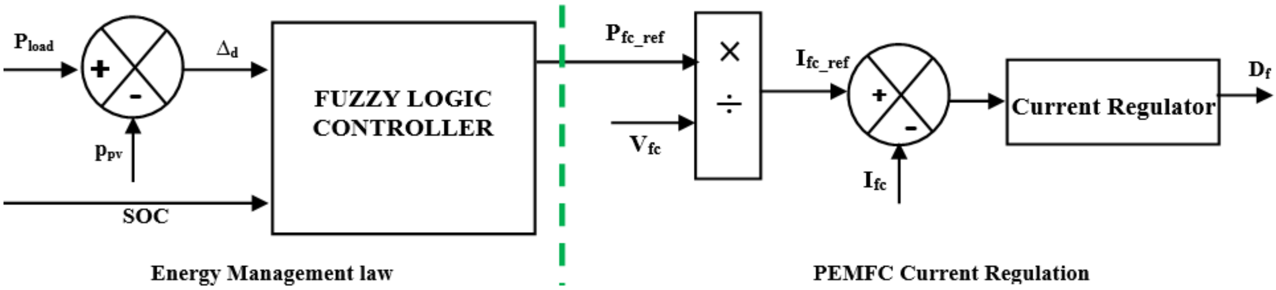


Fig. 11. PEMFC generating DC/DC converter control structure

Results and discussion. Throughout the simulation, in order to monitor and manage the operation of the proposed system at varying load values (ranging from around 0 to 14 kW) as shown in Fig. 12 the system is intended to provide sufficient power to a random three-phase dump load. In MATLAB/Simulink the suggested configuration and hybrid energy management system are developed and simulated for a total simulation period of 300 s.

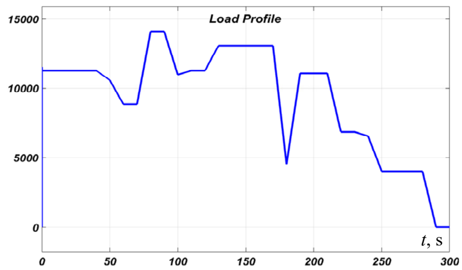


Fig. 12. Load profile

Figures 13-15 show the irradiation profile, PV current, and PV power consumed, respectively. The PV is assumed to be operating at a constant temperature of 25 °C, and about the irradiance value is designed to indicate meteorological conditions, solar intensity, nighttime, and whether or not shade is present.

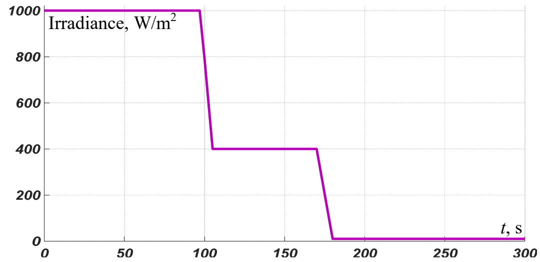


Fig. 13. Irradiation profile used throughout the simulation

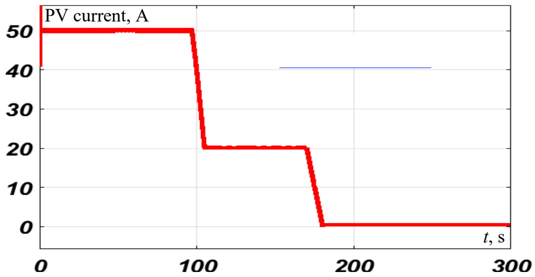


Fig. 14. PV current

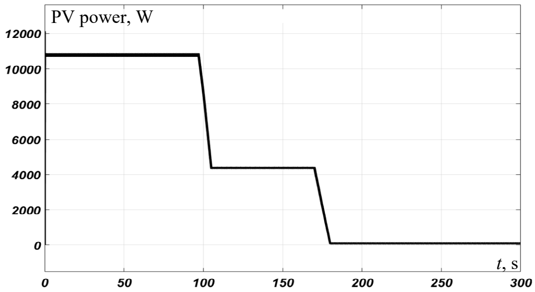


Fig. 15. PV power

The irradiance value is 1000 W/m^2 according to day light at the start (at 0 s) of the simulation period, with solar panels producing a maximum power of 10.8 kW, because the temperature T = 25 °C is expected to be constant, during this time, the solar panels cover the load requirement of 11.08 kW with the aid of the FC's low power, and the battery maintains its initial SOC, which is 65 %. At 40 s, the PV power generated surpasses the load requirement, since the irradiance value remained constant at 1000 W/m^2 when the load power decreased, the excess PV power production is utilized to charge the battery and SC, in this instance, the PV power interferes in regulating and controlling of charging/discharging of the batteries, and also the regulation and controlling of the FC current, at the same time, the FC's power consumption is reduced. At 70 s, (there is no excess power since the load demand exceeds the PV power generated), the load power began to rise and the solar panels continue to produce the greatest amount of energy possible, it is insufficient to meet the load demand of 14 kW, because of its sluggish response of the FC and battery, the SC begins to supply the load with the required power (for its quick response).

At 98 s, and when the irradiance value falls to 400 W/m^2, the amount of power generated by the PV panels is decreasing, in this situation, the EMS calculates the difference between the load power and the PV power. And then the updated values of the FC current and battery charge/discharge current are determined. As both the PV, FC, and battery begin to provide power to the system based on the FC reference current and battery discharge current, the SC power is reduced, and the load power is provided mostly by the PV, FC, and battery, with the SC providing a small portion of the load power. The irradiance value drops to 0 W/m^2 after 180 s (the PV power is 0 W) and the load power began to decline once more, because of the charge/discharge responsiveness of the SC, the SC begins to give power to the load sooner than the FC and battery, the SC power is reduced once again, with the FC and battery providing the majority of the load power. At 220 s the load continues to decrease as the FC alone becomes sufficient to meet its demand. At 270 s, as the load continues to decrease, the FC covers the load requirement, in this situation the extra power is used to charge the battery once more. When this time period comes to a close, the load power is zero, and the FC provides power to charge the battery and the SC. Figure 16 depicts the performance of all power sources during the course of the simulation, from 0 to 300 s.

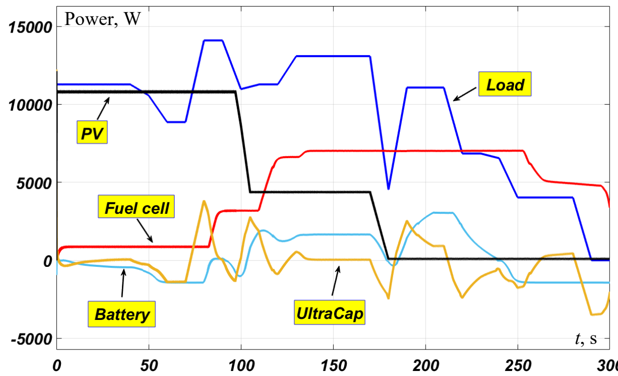


Fig. 16. Performance of all power sources

Figure 17,*a* depicts the battery's SOC percentage, which at the beginning of the simulation maintains its initial value of 65 %, and in the 40 s, through the lack of power demand for the load, through the lack of power demand for the load, the battery is charged through the excess solar panels power 65.5 %, and by raising the load's demand power, the battery is drained to support other power sources through the specified strategy of supplying the load with its required power until it reaches a value of 63.6 % at 170 s. The load increases again and the battery is discharged until it reaches its minimum value of 62.7 % at 280 s. At the end of the simulation, SOC % is increased to 63.5 % with decreasing load (300 s).

Figure 17,*b* depicts the battery's output power, battery power is represented negatively owing to the charging mode, then it becomes positive when the load rises and the battery begins to give power to the system. Figure 17,*c* depicts the battery voltage, whereas Fig. 17,*d* depicts the battery current. These 2 graphs illustrate that at maximum battery output power and maximum discharging current, the lowest battery voltage exists, and when the battery's output power and discharge current are at their lowest, the maximum battery voltage value exists.

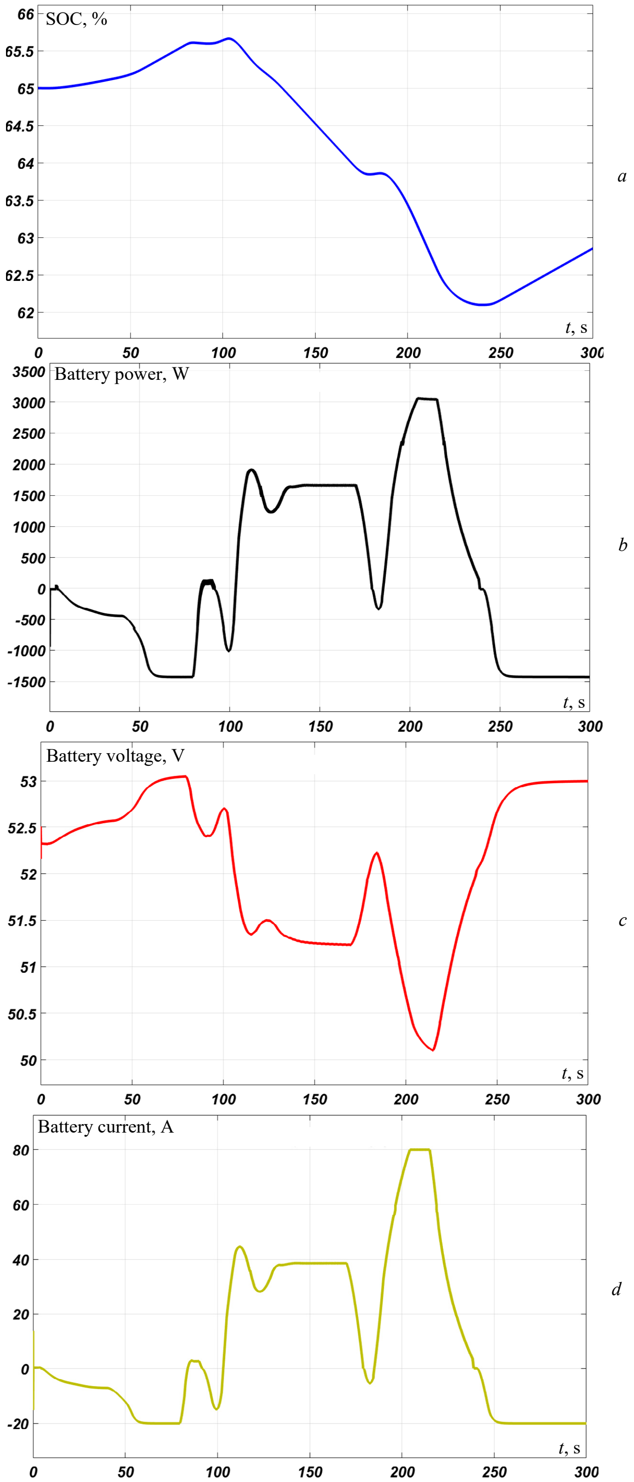
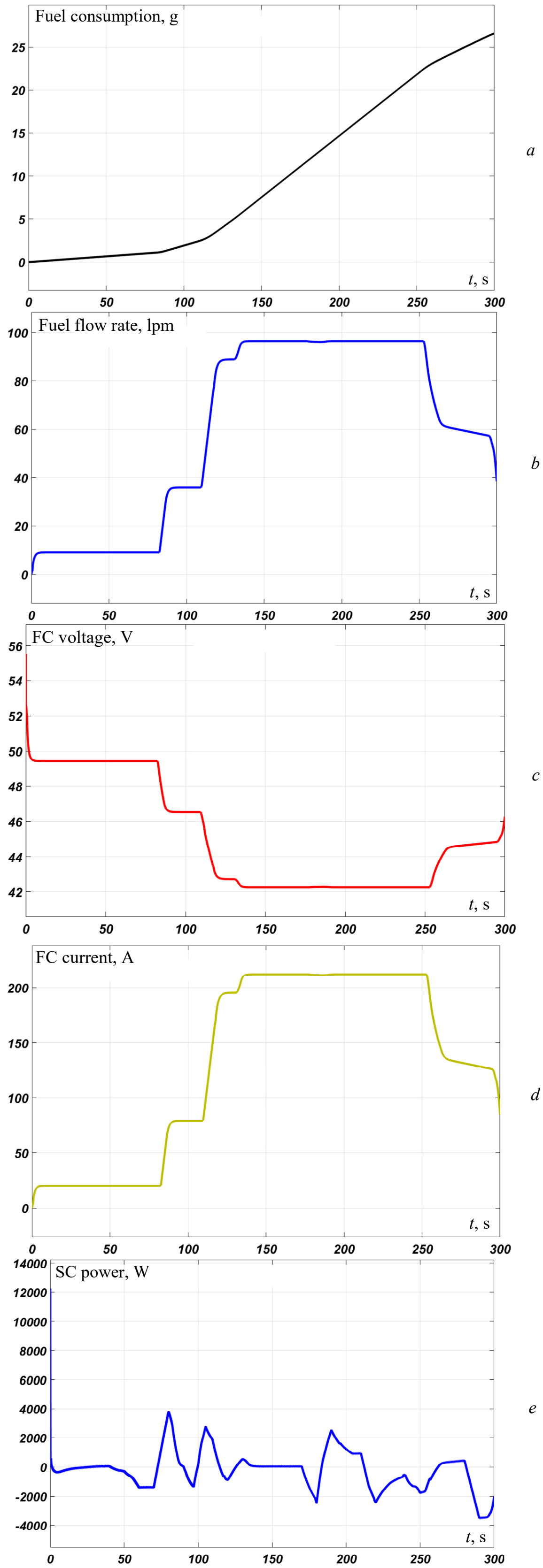


Fig. 17. *a* – battery SOC; *b* – battery power;
c – battery voltage; *d* – battery current

Figure 18 depicts the FC values over 300 s (the simulation period). Figure 18,*a* illustrates the hydrogen fuel consumption, which reaches 27 g at the completion of the simulation. The fuel flow rate is shown in Fig. 18,*b*. The FC voltage and current are depicted in Fig. 18,*c*,*d*. The highest current FC is obtained at maximum load power, lowest SOC value, and minimal PV power (Fig. 18,*e*,*f*,*g*).

The findings of the rule-based fuzzy logics technique needed to be validated, for that we checked the H2 consumption results and the battery's ultimate SOC from the energy management system, which is used to govern hybrid energy sources, this is accomplished by comparing these findings to the same results obtained in the same scenario but with the management flowchart of the REHPS. According to the current study, the flowchart of management in MATLAB function was set up with three inputs, which were P_{load}, P_{PV}, and battery SOC, while the output was set to be the FC reference current.



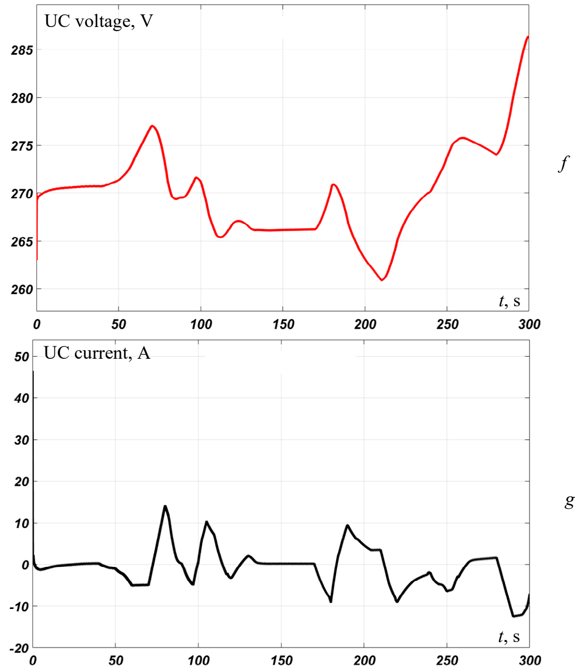


Fig. 18. *a* – hydrogen fuel consumption; *b* – fuel flow rate; *c* – FC voltage; *d* – FC current; *e* – SC power; *f* – UC voltage; *g* – UC current

Figures 19,*a*,*b* depict a comparison of 2 control techniques for SOC and hydrogen consumption. Table 7 shows the results of the comparison.

Table 7

Comparison among considered control strategies

Method	Fuzzy logic strategy	Management flowchart
Hydrogen consumption, g	26.5	29.1
SOC, %	[62.2-65]	[59.2-65]

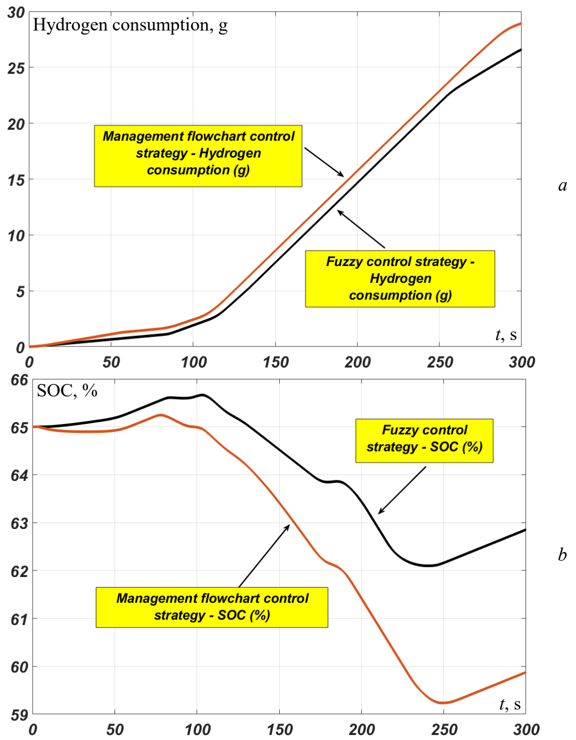


Fig. 19. *a* – comparison results H2 consumption; *b* – comparison results battery SOC

According to this study, the management flowchart control approach is the most hydrogen-consuming, while the fuzzy control strategy consumes the least. The fuzzy logic technique achieves low hydrogen consumption and a high SOC value at the same time, as well as a long life cycle and good overall system efficiency.

When compared to the management flowchart, which takes longer to charge, the fuzzy control method has a faster charge time. When it comes to discharging, fuzzy has a favorable outcome with less discharge time. On the other hand, management is quick to discharge.

Conclusions. It has become necessary to have an energy management system through the use of effective strategies to control and monitor the behavior and dynamics of hybrid energy sources. This paper presents the fuzzy control strategy for the power management of the hybrid renewable energy systems (photovoltaic/fuel cell/ supercapacitor/battery), this hybrid power system is able to solve the lone source problem in addition to providing the load with the energy it needs with continuity and stability, PV provides the main power to the load and in case of shading and night, the fuel cell intervenes to meet the power shortage, and to solve the problem of slow response to fuel cell during the rapid change of load power we added the battery and supercapacitor to the system, which also maintains the stability of DC voltage at its reference value. The proposed strategy worked to reduce hydrogen consumption and improve the battery state of charge, proving the feasibility of the management technique proposed in this study, fair, and effective. Simulation results are developed in MATLAB/Simulink environment to demonstrate the effectiveness of the fuzzy control strategy performance in different loading conditions; the results prove that the fuzzy control strategy performs better than the management flowchart control strategy under the same operating conditions in terms of hydrogen consumption and battery state of charge. In this work, the values of simulation parameters were carefully selected for future practical investigation. In order to improve the system in future research, it is suggested to focus on exploiting the excess energy by using it in the production of hydrogen by connecting an electrolyzer, and there is always room to improve energy management strategies for more efficient performance.

Conflict of interest. The authors declare no conflict of interest.

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