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M. Ali Moussa, A. Derrouazin, M. Latroch, M. Aillerie

A hybrid renewable energy production system using a smart controller based on fuzzy logic

Introduction. This article proposes an improved energy management and optimization system with an intelligent economic strategy based on fuzzy logic technology with multiple inputs and outputs (I/O). It is used to control hybrid electric energy sources built around photovoltaic solar panels, wind turbine and electric energy storage system assisted by the electric grid. **The novelty** in this work that solar photovoltaic, wind turbine and storage system energy sources are prioritized over the grid network which is solicited only during adverse weather conditions, in order to supply a typical household using up to 4,000 Wh per day. In addition of that, the surplus of renewable energy produced during favorable climatic condition is used to produce hydrogen suitable for household heating and cooking using electrolyzer system. **Purpose.** Development of improved energy management and optimization system with an intelligent economic strategy based on fuzzy logic technology. This system is embedded on Arduino 2560 mega microcontroller, on which the fundamental program of fuzzy logic and the distribution of events with all possible scenarios have been implemented according to a flowchart allowing the management of the hybrid system. **Methods** as well as a parametric search and a simulation to characterize the system, are carried out in order to put on the proposed techniques to ensure continuous accommodation at home. **Results.** The proposed system results confirm their effectiveness by visualizing the output control signals from the electronic switches. **Practical value** of which transmits power through a single-phase DC/AC converter to power the AC load for the accommodation. References 20, figures 9.

Key words: hybrid energy system, renewable energy, battery storage, fuzzy logic, smart management.

Вступ. У статті пропонується вдосконалена система керування та оптимізації енергоспоживання з інтелектуальною економічною стратегією, заснованою на методі нечіткої логіки з декількома входами та виходами. Вона використовується для керування гібридними джерелами електричної енергії, побудованими на основі фотоелектричних сонячних панелей, вітрових турбін та системи зберігання електричної енергії за допомогою електричної мережі. **Новизна** роботи полягає в тому, що сонячні фотоелектричні, вітряні турбіни та джерела енергії системи зберігання енергії мають пріоритет над електромережею, яка запитується лише за несприятливих погодних умов, щоб забезпечувати типове домашнє господарство до 4000 Вт·год на день. Крім того, надлишки відновлюваної енергії, що виробляється у сприятливих кліматичних умовах, використовуються для виробництва водню, придатного для опалення та приготування їжі за допомогою електролізера. **Мета.** Розробка вдосконаленої системи керування та оптимізації енергоспоживання з інтелектуальною економічною стратегією, що заснована на методі нечіткої логіки. Ця система вбудована в мегамікроконтролер Arduino 2560, на якому реалізована головна програма нечіткої логіки та розподілу подій з усіма можливими сценаріями за блок-схемою, що дозволяє керувати гібридною системою. Зазначені **методи**, а також параметричний пошук та моделювання для характеристики системи реалізуються для того, щоб застосувати запропоновані методи для забезпечення безперервного проживання у будинку. **Результати.** Результати реалізації запропонованої системи підтверджують їх ефективність візуалізацією вихідних сигналів керування від електронних перемикачів. **Практичне значення** полягає у передачі потужності через однофазний перетворювач постійного струму у змінний для живлення навантаження змінного струму для житлових приміщень. Бібл. 20, рис. 9.

Ключові слова: гібридна енергетична система, відновлювана енергія, акумуляторна батарея, нечітка логіка, інтелектуальне керування.

Introduction. To avoid the problems of pollution in the production of electricity, alternative solutions can be photovoltaic (PV), wind, or even hydroelectric sources. In addition, the distribution networks cannot be sufficient to supply electricity to the entire world population: whether they are in the mountains or on an island, in the least inhabited regions or in the middle of the desert, the sites difficult to be access or very isolated cannot always be connected to the network, for lack of technical solutions or economic viability. However, being able to be sized for domestic use, renewable energy sources lend themselves particularly well to the production of electricity called isolated sites, or micro-grids. They are then often associated with batteries, which ensure the storage of energy in the event of excess production, or to compensate for the momentary lack of power during peak consumption [1-5].

Hybrid energy systems (HES) combining several sources, such as renewable energy systems (RES), the national distribution network (the historical network), traditional energy sources and storage systems are generally considered as a solution for the future is efficient and reliable, many analyzes (planning and sizing) have been performed on single-source renewable energy sources, with the main objective being to determine the best system configuration for efficient and safe operation.

They can be developed in a substantial way for urban electrification or isolated (rural) sites. When, the cost of grid extension of rural electrification is prohibitive due to geographic isolation, low population density, or limited financial resources. In both cases, the issue of energy management, particularly in terms of resource control and efficiency, becomes essential. In this, it has become in the space of a few years, one of the eminently strategic subjects. Its implementation is both complex and exciting as the prospects are promising, especially in relation to smart grid technologies.

A different hybrid energy system has been studied in many research papers [6-18]. The authors in [19] are proposing to realize a technical-economic capacity of a hybrid renewable energy system (HRES) to occupy the energy demand of a university site in the Himalayan state of northeastern Sikkim, and also the other aspect of exploring the electrical voltage of other renewable energy resources such as biogas and syngas and hydrokinetic energy, in addition to a solar-wind hybridization mainly carried out in the resource-rich urban planning territory of the east of the Himalayas. The authors in [20] operating a hybrid off-grid renewable energy system (HRES) for an institution's huge high-rise urban development in Nigeria. The exploitation is based on a comparison of the employment of a single

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criterion with a combination of factors in determining the most feasible energy system. A wind turbine, a diesel generator, a PV system, and a battery storage system are all part of the proposed HRES – Multiple Energy Resources Hybrid Optimization (HOMER).

The goal of the paper is the development of improved energy management and optimization system with an intelligent economic strategy based on fuzzy logic technology.

This paper is a continuity of previous work [17], where a complex hybrid energy system is studied, sized, optimized and a smart router system is achieved to manage electric energy flow based on fuzzy logic techniques. The added value in this contribution is the implementation of artificial intelligence in hardware based on Arduino type microcontroller which built on multi analog/digital inputs/outputs and PWM (pulse width modulation technique), from where electronic switches command' signals are highlighted and discussed.

Hybrid energy system design. The proposed hybrid energy system HES is a combination of solar energy conversion system comprising solar panels with integrated a MPPT (maximum power point tracker) converter, wind energy conversion system built on direct current outcome converter permanent magnet synchronous wind turbine and then a storage system with acid-plumb batteries.

The equipment of the dwelling operates at 220V 50 Hz with an optimal use of the energy thanks to economic LED lighting lamps and zenithal daylight. The standard equipment used in this house consumes total amount energy about 4 kWh per day with a peak of 660 W when using the entire electric component at the same time. The system energy flow is managed by a smart energy router system based on artificial intelligence using fuzzy logic algorithm [8].

Figure 1 shows the global hybrid system with the combination of solar PV, wind turbine and storage within all the regulators.

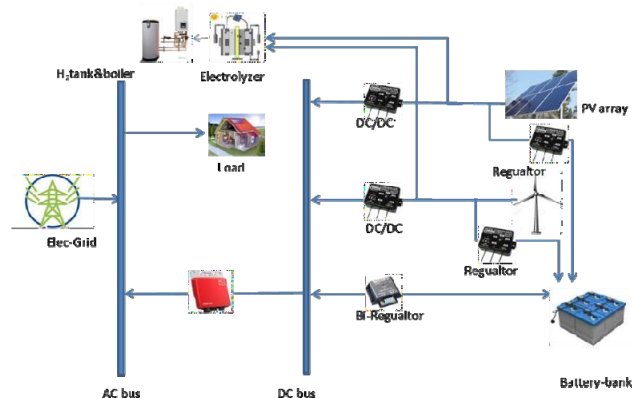


Fig. 1. Synoptic of the proposed HPS (Hybrid Power System)

Components of the hybrid energy system. As part of our work, solar energy has been favored as a primary renewable energy source because of the chosen site at north of Algeria. The selected PV panels are polycrystalline type delivering, each of them, an output summer voltage amount of 30.7 V and developing 250 W nominal power. The panels are equipped with MPPT regulators [9] and connected in parallel to obtain an

overall power of 2 kW. This choice was pointed due to their quality/price [9, 10]. The connection of the solar panels in parallel mode to multiply the output current and maintain a standardized output voltage at 24 V DC which is fed directly into the common DC bus of the system

Considering the case study, the instantaneous power cannot exceed, according to the established dimensioning and for the case of maximum of energy demand, the value of 660W. For this reason and taking into account the wind potential in the study area, our choice was oriented towards small, inexpensive EO-24-1000R-UGS-Silent three- bladed wind turbine with 2.9 m rotor diameter, developing nominal power up to 1 kW.

Because of their availability on the market in different capacities, as well as their proven effectiveness, especially in the automotive field, our choice was pointed to an electrochemical lead-acid storage type, although the cycling behavior of the latter is not important compared to other technologies such as lithium. But they have the advantage of an affordable investment, much simpler maintenance and their resistance to high electrical capacity demands. What joins our goal to develop at low cost the use and generalization of the renewable energy in our country.

Given the uncertain nature of renewable resources, particularly solar and wind, deficits and excess energy production can be observed. For the second situation, the excess of energy is often harmful for the stability of the system. For that, several works proposed an evacuation of this surplus produced electric energy in a specific load which one calls dump load [17]. Previous work in reference [18], proposed to recover this surplus of energy production, from only renewable sources especially during favorable climatic conditions, and to exploit it to produce hydrogen with the help of an electrolyze device in order to be useful for household heating and cooking

Fuzzy logic controller. The intelligent controller, as shown in Fig. 2, with its multiple image entries of the available power profiles as well as the outputs such as grid to load (G2L), PV to load (PV2L), wind turbine to load (W2L), battery storage to load (B2L), PV to battery storage (PV2B), wind turbine to battery storage (W2B), electric grid to battery storage (G2B), PV to electrolyzer (PV2E) and wind turbine to electrolyzer (W2E), represents the routes pointed by the intelligent controller allowing renewable and conventional energies transfer to the load, to the electrolyze and the storage. The Fuzzy Logic System Controller (FLSC) is designed according to well-defined basic conditions allowing the best functioning of the overall system for all its scenarios and possible operating points by considering the logical constraints initially fixed by an expert [19] as:

- the principal sources of load feeding are PV and wind energy, followed by battery storage and finally the electrical grid;
- batteries are replenished by the grid only when solar and wind energy levels are low;
- when all other sources of energy are off, the power grid powers the load.

Only PV solar energy and a wind turbine are used to power the hydrogen production system. These instructions and recommendations initially dictated for suitable operation of the intelligent controller are shown

in the simplified diagram below in Fig. 3, which generate a set of 81 rules. The formulation and implementation of these constraints are established using fuzzy logic tools and performing dozens of combinations with the three levels – H (high) 3, M (medium) 2 and L (low) 1. On the other hand, the logical results of the FLSC are imposed for each combination at the entrance of the four energetic states (charge, solar, wind, storage).

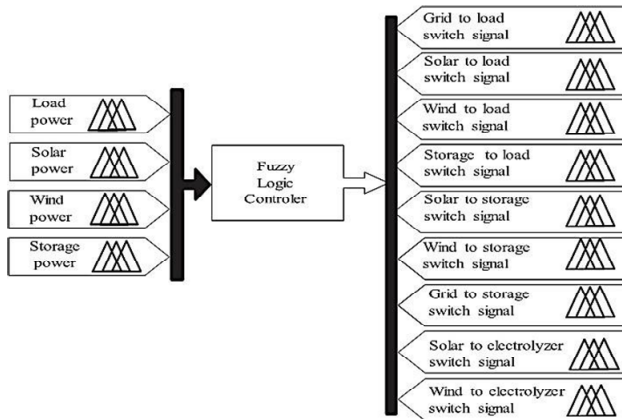


Fig. 2. FLSC intelligent controller diagram (fuzzy logic smart controller)

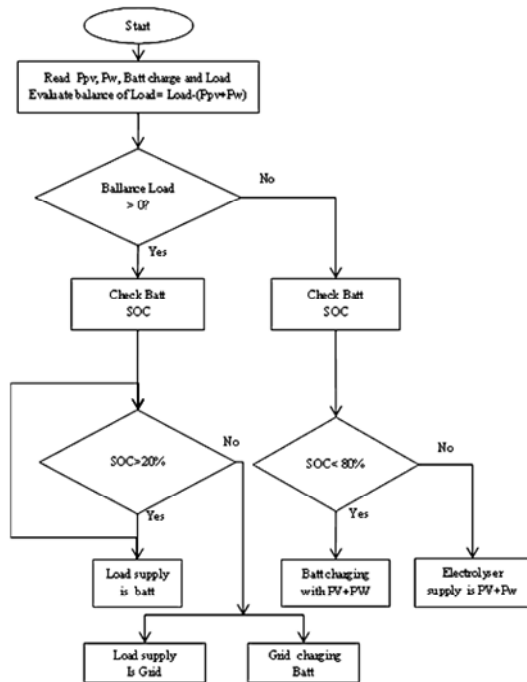


Fig. 3. Operational flowchart of the HPS-FLSC (hybrid power system – fuzzy logic system controller). Here SOC is the state of charge

FLSC hardware implementation. In the last section on a previous work [17], we presented a simulation work on MATLAB fuzzy logic, the results obtained are detailed, where the outputs of the FLSC manage the PWM blocks in order to control the command signals duty cycle of electronic switches.

In the goal to move from simulation to emulation, we successfully implemented the topology of smart controller under Arduino mega 2560 microcontroller, which is built on more eeprom memory capacity, over than fifty analog and digital I/O and thirteen ready pulse width modulation PWM outputs. That why we pointed this type of hardware.

It corresponds wildly to the presented FLSC controller, which needs to control nine electronic switches. The work consists to convert the MATLAB fuzzy logic FLSC program to the open-source Arduino Software (IDE) sketch. The entries are images depicted of the inputs energy profiles like the load demand, the PV, the wind turbine and the capacity of the batteries.

Figure 4 presents the electrical scheme of the controller using Proteus electronic software where all connections with the microcontroller are shown. The outgoings are connected to LEDs displaying the level of the output PWM signal depending on the four inputs power profiles' states exactly as illuminated in precedent section.

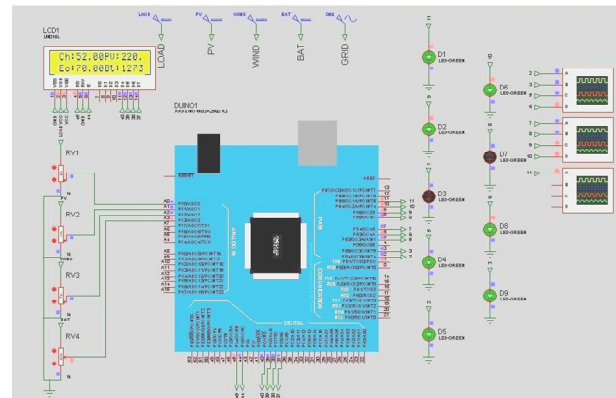


Fig. 4. Electrical scheme of the Arduino-FLSC controller

Using MATLAB tools for simulation, data power profiles for solar and wind energy, as well as battery storage, were imposed on the system during a typical day in May to ensure the reliability of the intended FLSC controller [20]. The load supplies vary from month to month. Summer is the hottest season in the northern hemisphere. As a result, the load demand for those months would be reduced, and for the other three seasons, more gloomy days with lower temperatures are projected. As a result, due to the possibility of heating and additional lights, these months would have a higher electricity demand. Figure 5 depicts the power profile inputs as they change during the course of a typical day.

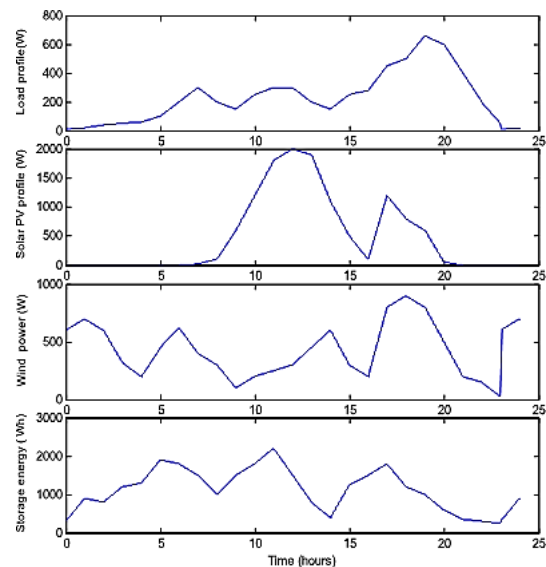


Fig. 5. Power profiles versus time of the hybrid power system (HPS) during 24 hours

Results and discussion. Figure 6 shows the FLSC defuzzification findings utilizing the corresponding membership functions in MATLAB Fuzzy tools. The resulting analog signals oscillate between 0 and 1, and PWM techniques are used to convert each FLSC output to a square signal with a variable duty cycle and fixed frequency. Each command signal is injected into a matching electronic switch, and all of the switches' selected quantities of available energy sources are added together and converted to AC current via the DC/AC converter to fulfill habitation appliances. Excess DC-produced renewable energy is used directly to make hydrogen. Based on these results [18, 20], the implementation of the hardware consists to conversion and adaptation of the validated MATLAB program in the IDE platform where command lines are processed and compiled in IDE-Arduino microcontroller software.

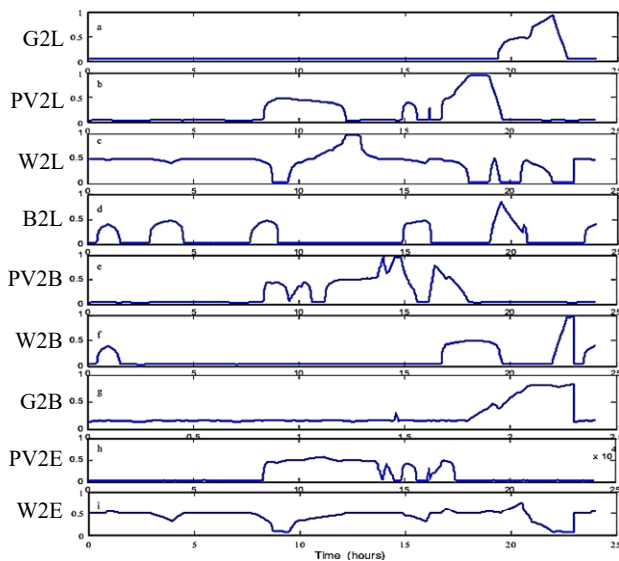


Fig. 6. FLSC outcome switches command signals

In order to validate the operative FLSC program after many steps from MATLAB to Ide-Arduino, a simulation in Proteus software is scheduled and rule no. 2 is tested, where the input sand the outputs of the FLSC-Arduino obey to a series of codes as mentioned in the framed line [1.1.1.2, 1.1.1.2.1.1.1.1.1] shown in the Fig. 7 below. The settings of the input levels are assumed by potentiometers which are visualized on LCD display in Fig. 4 as:

- load (Ch): 52 W of 660 W → Low L → level 1,
- PV: 220 W of 2000 W → Low L → level 1,
- wind turbine: 70 W of 1000 W → Low L → level 1,
- battery: 1273 W-h of 2400 W-h → Medium M → level 2.

With the same reasoning, the FLSC-Arduino outcomes are shown in the Fig. 8 under PWM command signals, which are ready to excite the electronics switches. The width (duty-cycle) of the 9 outputs from the top to the bottom correspond widely to the suite of the series line [1.1.1.2; 1.1.1.2.1.1.1.1.1]→[L.L.L.M; L.L.L.M.L.L.L.L.L]

The top to the bottom correspond widely to the suite of the series line: [1.1.1.2; 1.1.1.2.1.1.1.1.1]→[L.L.L.M; L.L.L.M.L.L.L.L.L]

Figure 9 presents a screenshot of the real cabling and running hardware.

```
[System]
Name='FLSC49-15mars'
Type='mamdani'
Version=2.0
NumInputs=4
NumOutputs=9
NumRules=80
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Rules]
1 1 1 1, 2 1 1 1 1 1 3 1 1 (1) : 1
1 1 1 2, 1 1 1 2 1 1 1 1 1 (1) : 1
1 1 1 3, 1 1 1 2 1 1 1 1 1 (1) : 1
1 1 2 1, 1 1 2 1 1 2 1 1 1 (1) : 1
...
```

Fig. 7. FLSC Fuzzy Inference System file screenshot (codification of rule no. 2)

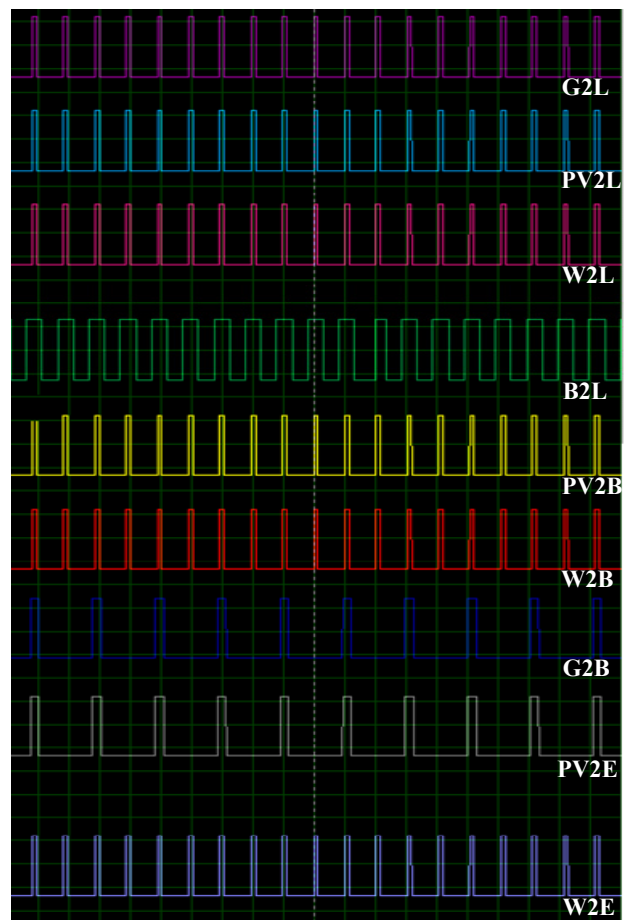


Fig. 8. PWM signals from FLSC-Arduino. From Top to Bottom: the multiple outputs are G2L, PV2L, W2L, BAT2L, PV2B, W2B, G2B, PV2E, W2E

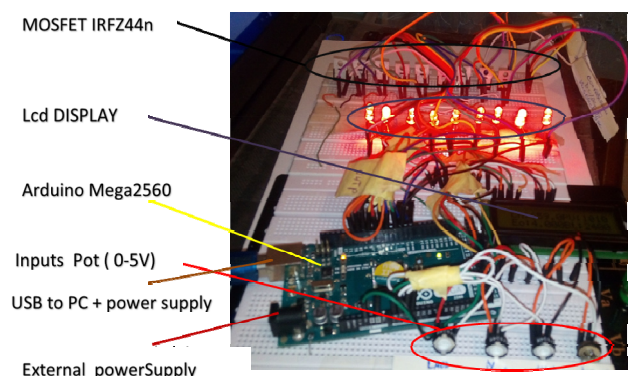


Fig. 9. Image of the FLSC-Arduino on a test plate

Conclusion.

A household hybrid energy system with solar-wind sources and storage was constructed and simulated using fuzzy logic smart controllers. 81 operating rules were designed and applied in the system for backup and energy requests as part of the management plan. The fuzzy logic program processed on MATLAB has been adapted and converted to IDE-Arduino program which is implemented in microcontroller type Arduino mega 2560. The validation of the operating FLSC under the hardware was successful and outcomes correspond likely to the rules and constraints imposed by the expert. The FLSC-Arduino output PWM signals can excite directly the electronic switches in order to convey simultaneously the available energy from the sources to the user.

Conflict of interest. The authors declare that they have no conflicts of interest.

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