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Design methodology of smart photovoltaic plant

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ABSTRACT

In this article, we present a new methodology to design an intelligent photovoltaic power plant connected to an electrical grid with storage to supply the laying hen rearing centers. This study requires a very competent design methodology in order to optimize the production and consumption of electrical energy. Our contribution consists in proposing a robust dimensioning synthesis elaborated according to a data flow chart. To achieve this objective, the photovoltaic system was first designed using a deterministic method, then the software "Homer" was used to check the feasibility of the design. Then, controllers (fuzzy logic) were used to optimize the energy produced and consumed. The power produced by the photovoltaic generator (GPV) is optimized by two fuzzy controllers: one to extract the maximum energy and another to control the batteries. The energy consumed by the load is optimized by a fuzzy controller that regulates the internal climate of the livestock buildings. The proposed control strategies are developed and implemented using MATLAB/Simulink.

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1. INTRODUCTION

To solve the global warming potential and depletion of fossil fuels, the Paris agreement was adopted through the 21st conference held in Paris, France in December 2015. In response to this, the Algerian government plans to launch several projects by 2020, with a total capacity of 800 MW. During the period 2021-2030, PV plants of 200 MW per year are expected to be built [1].

The production of electricity with a photovoltaic system connected to the grid is of great interest to countries with high solar potential. However, the design of such a system must be taken correctly in order to optimize the collection of radiation by the photovoltaic cells and increase the efficiency of the system. The use of smart technology can improve the operation of these plants. Therefore, it helps to improve the quality of service of the electricity network, which has been insufficient in recent years, due to the great demand on electricity. In summary, this work concerns the design and optimization of the operation of a smart photovoltaic generator used to supply an industrial campus for laying hens, located in western Algeria. These sites were created in the 1990s by the Algerian government to improve poultry production [2]. It contains four centers, two for the preparation (breeding) of the laying hen and two laying centers. Each center is made up of 10 livestock buildings with an area of 80x12 m^2, i.e. 40 buildings for the entire site. Each building is equipped with an electrical control cabinet. To better undertake this study, a survey was launched on the requirements of the company, the conditions of the site to design the photovoltaic system and to understand the techniques of raising laying hens. However, we concluded that such a project requires a very competent design methodology in order to optimize the production and consumption of electrical energy and thus reduce investment costs. Therefore, we have proposed a robust dimensioning of the photovoltaic system as shown in the flowchart in Figure 1. It contains three steps. First for the dimensioning we used a deterministic approach based on the worst month of the year [3]. To validate the design results and determine the optimal configuration, the Homer design software [4] was integrated in the second phase of this work. Indeed, the interpretation of the HOMER results allowed us to validate the sizing steps carried out previously and to have an optimal configuration of the system in order to ensure the best compromise between technical feasibility and economic profitability. The third design phase was devoted to the optimization of the energy produced and consumed.

However, to optimize the energy produced, we have proposed the use of a fuzzy intelligent regulator to extract the maximum MPPT power [5] and, another fuzzy regulator to charge and discharge the batteries because this device is very sensitive in these installations. In addition, the building must create an environment favorable to the breeding of poultry, that is to say meeting their physiological needs. These requirements are determined by temperature, air speed and humidity [6], [7]. It therefore influences the profile of electrical energy consumption and the equipment operating service. To optimize the energy consumed, we used intelligent temperature and humidity controllers. These controllers are very effective and robust in maintaining the internal climate according to the standards required for raising chickens. The MATLAB/Simulink software was used for the simulation of all the intelligent control procedures [8].

2. RESEARCH METHOD

2.1. Design methodology

In general, the design methodology of a photovoltaic system is based on standard approaches [9]-[11]. However, each designer has to design his own algorithm that depends on the nature of the system to be sized, the functional relationships between the system components, the external influences and the technology used. Our design methodology is summarized in the flowchart shown in Figure 1.

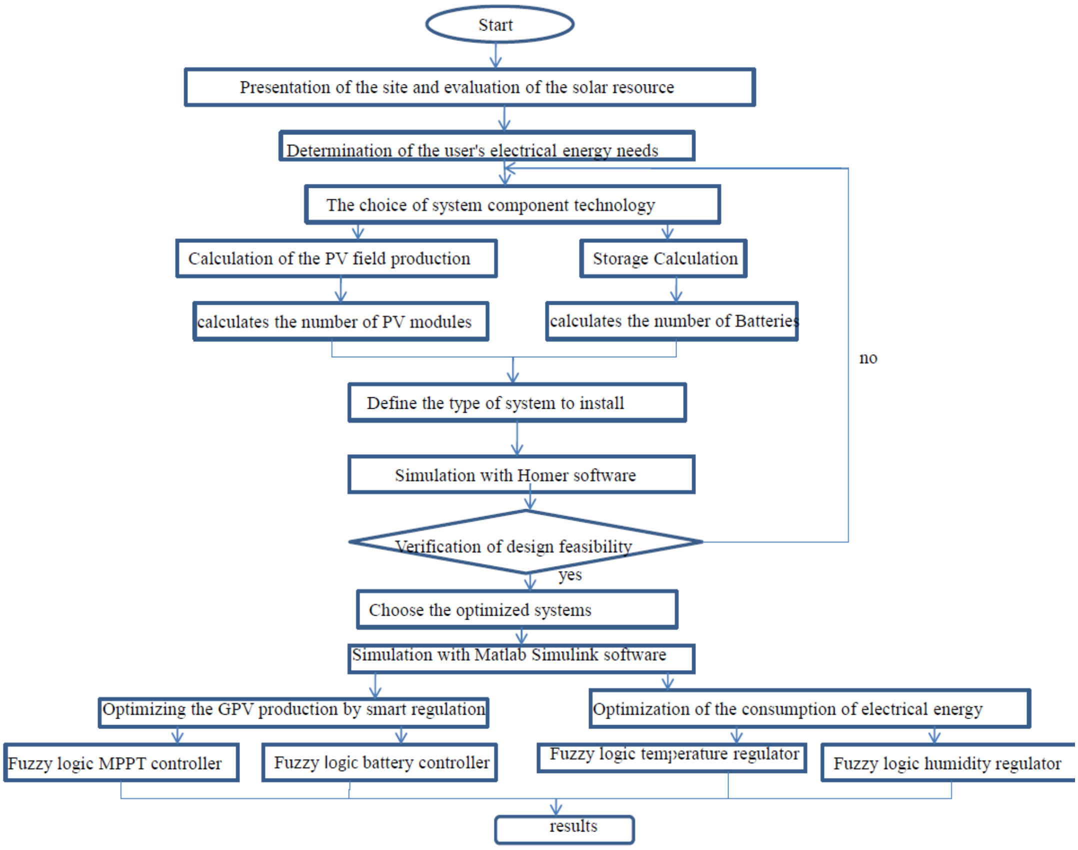


Figure 1. The flowchart of our methodology

This structure includes the following main phases:
First phase: classic dimensioning;
Second phase: verification of the feasibility of the design with the "Homer" design software;
Third phase:

a. Optimization of the production of the photovoltaic system;
b. Optimization of electrical energy consumption by intelligent control of the interior climate of the livestock building

2.2. Details of the various phases

2.2.1. First phase: classic sizing

a. Presentation of the site and evaluation of the solar resource

Geographical coordinates of the breeding site Latitude: 35 degrees 12 minutes north, Longitude: 1 degree 15 minutes East, Time: GMT +1: 00. The ideal orientation of a photovoltaic panel obeys the rule of orienting it towards the equator. Since latitude of our installation is (35°), the inclination will be $\alpha=35+10=45°$.

b. Meteorological data

For this study, technical data is collected from the NASA global satellite [11]. It should be noted that the average monthly solar radiation in the region exceeded 7.14 kWh/m^2/day in June and decreased to 2.25 kWh/m^2/day in December with an average of 4.72 kWh/m^2/day. Therefore, the most unfavourable month was taken into account in the design procedure [12], [13].

c. The determination of the user's electrical energy needs

However, the electrical energy E consumed by the breeding center is calculated by (1).

$$E_t = \sum_{i=1}^{n} P_i t_i \tag{1}$$

With: P_i= electrical power of a device expressed in Watt (W),
t_i= duration of use of this device in hours per day (h/d)

The peak power of the panels of two buildings is obtained by:

$$E_{zone} = N_e * P_c * C_P \tag{2}$$

E_{zone} (kWh/d)= the energy consumed
Ne=2.25 h: the period of solar irradiation of the worst month (December)
Cp=0.6: the equivalent coefficient of losses inherent in the whole process of energy conversion.

d. Dimensioning of electrical energy storage

The objective of the sizing of the Battery Park is to have a good yield, a long life and a low investment cost [14]. In general, the main characteristics of an accumulator are:

- The voltage at the terminals of an accumulator element;
- The capacity provided by the manufacturers for a given discharge regime in hours (C20 or C100);
- The discharge depth Pd which represents the maximum discharge threshold.

The calculation of the usable and nominal capacity:
C_U: Useful capacity of the battery in *Wh*,
Nja: Number of days of autonomy without solar input (02 Days)
E_{zone}: Daily consumption of the zone in Wh/day
Rt: Temperature coefficient
The calculation of nominal capacity C_{nom} is given by

$$C_{nom} = \frac{N_{ja} * E_{zone}}{Pd \text{ x } Rt} \tag{3}$$

e. Define the type of system to install

The chosen configuration includes a photovoltaic generator with MPPT controller, a storage system with battery regulators, DC/DC converters, DC/AC converters, load and power grid as shown in Figure 2, [15], [16].

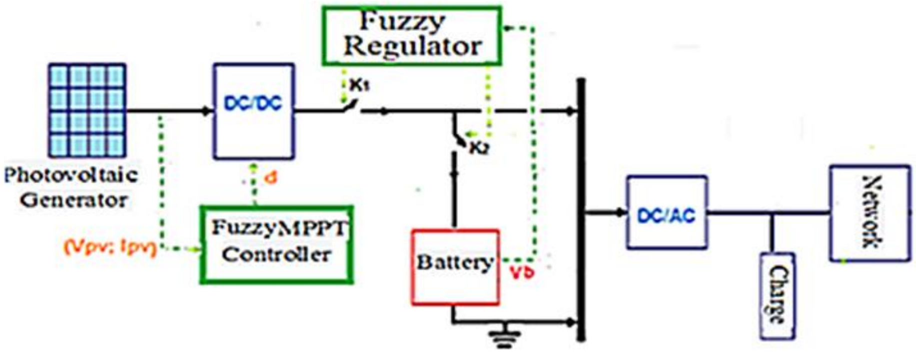


Figure 2. Scheme of the proposed photovoltaic system

2.2.2. Second phase: verification of design feasibility with "homer" design software

The designed system is introduced into the software by specifying the options of technology availability, component cost and resource availability. HOMER is a simulation and technical and economic optimization software for hybrid renewable energy systems. The method used by Homer gives us the reliability of the system by loss of power supply probability (LPSP) which is calculated for each configuration and the optimal configuration chosen is based on the minimum life cycle cost (LCC). The architecture of the photovoltaic power plant using the Homer interface is illustrated in Figure 3. Therefore, our main objective is to evaluate the feasibility of the studied PV system [17], [18].

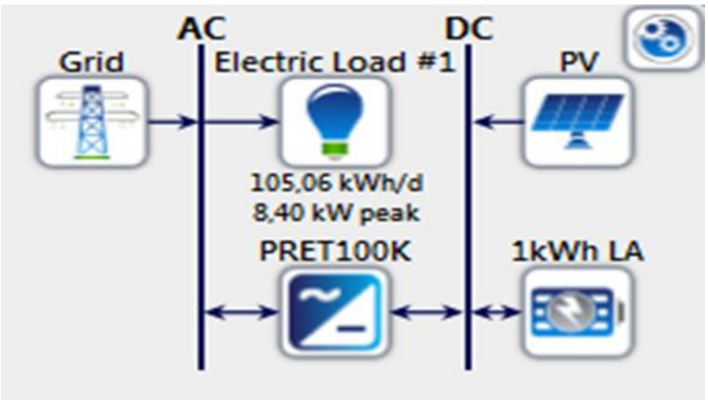


Figure 3. Architecture of the PV plant

a. How to use [18]

Place the site on the geographic map of the software to identify the coordinates. Assemble the components and choose their technical characteristics. Introduce or import the average consumption of the load per hour for each month of the year.

2.2.3. Third phase: Optimization of the energy produced and consumed by intelligent controllers

In short, fuzzy theory allows "the rigorous modeling and processing of imprecise, uncertain and subjective information". It allows the approximation of non-linear functions. It is therefore a theory that is perfectly adapted to the optimization problem we are dealing with in this work [19], [20].

a. Optimizing the GPV production by smart regulation

In this phase, we propose two fuzzy regulators. An intelligent MPPT controller will be used to extract the maximum power produced by the photovoltaic generator. Another fuzzy regulator will be used to control the charge and discharge of the battery. At the end, a check of the GPV generator operation will be performed to confirm the optimization phase of the energy production. The simulation is performed with MATLAB/Simulink [21], [22]. Figure 4 shows the proposed global system model.

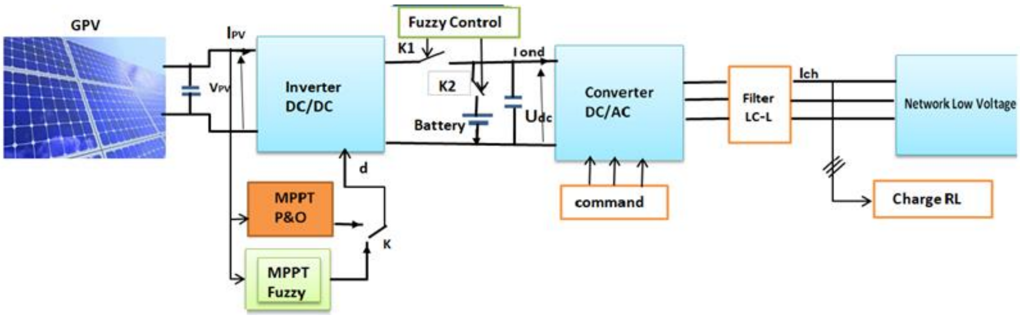


Figure 4. The proposed overall system model

1) Fuzzy MPPT controller

To determine the efficiency and transient response times of the fuzzy MPPT controller. The latter has been compared to a widely used conventional P&O controller [23], [24]. To implement the fuzzy controller, we need two inputs $\{\left(\frac{dP}{dV}\right)$ and $\left(\frac{d^2P}{dV^2}\right)\}$. The output is the change in the duty cycle Δd of the DC/DC converter. This value is used to determine the V_{MPPT} value at any time. Figure 5 shows the configuration of the selected fuzzy controller with these three phases.

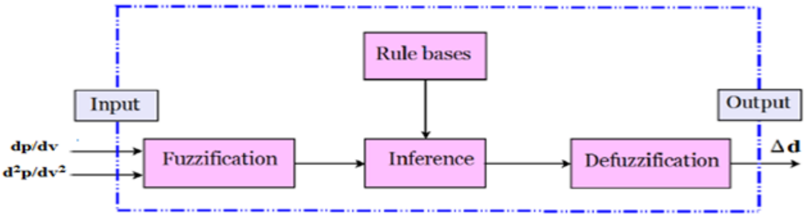
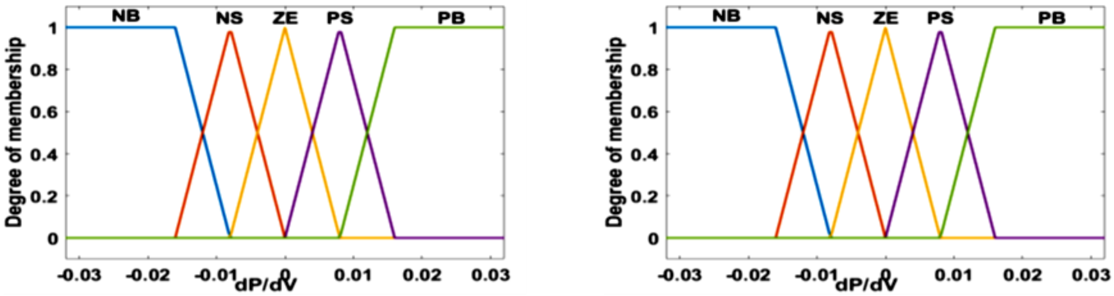


Figure 5. The proposed MPPT control using fuzzy logic

After obtaining the value of the output Δd at time k we calculate the new duty cycle and apply it to the DC/DC converter:

$$d\ \ (k) = d\ \ (k-1) + \Delta d\ \ (k)$$

Each fuzzy inputs and output variables are divided into five fuzzy sets, viz. negative big (NB), negative small (NS), zero (Z), positive small (PS), and positive big (PB). Figures 6 and 7 show its membership functions of fuzzy input and output variables, respectively. The control rules for this FLC controller is shown in Table 1.



(a) (b)

Figure 6. Membership functions of fuzzy input: (a)$\frac{dP}{dV}$, (b) $\frac{d^2P}{dV^2}$

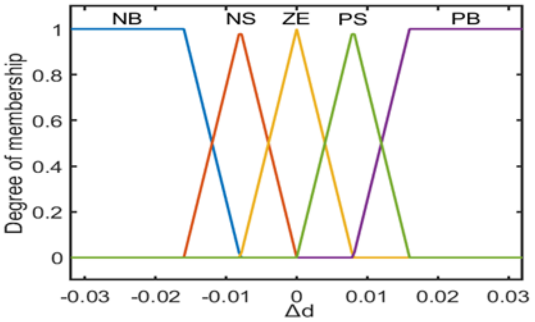


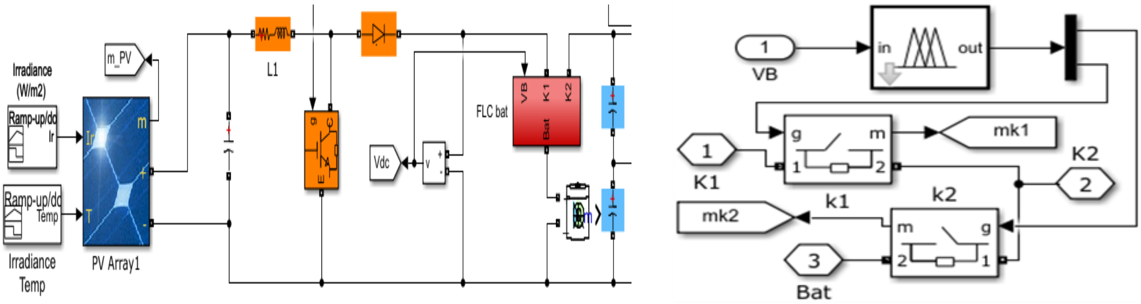
Figure 7. Membership functions of fuzzy output

Table 1. Rule base for the fuzzy ouput variable

Δd				$\frac{d^2P}{dV^2}$		
		NB	NS	ZE	PS	PB
dP/dV	NB	ZE	ZE	PB	PB	PB
	NS	ZE	ZE	PS	PS	PS
	ZE	PS	ZE	ZE	ZE	NS
	PS	NS	NS	NS	ZE	ZE
	PB	NB	NB	NB	ZE	ZE

2) Fuzzy charger battery

For the control of the battery charge and discharge regulator, a fuzzy model of Takagi-Sugeno [25], [26] has been chosen, which presents an efficient technique. The input is the battery voltage (Vb) and the outputs are the signals K1 and K2. The signal (K1) is the command of switch 1 between the GPV and the battery [0,1] and the signal (K2) is the command of switch 2 between the battery and the load [0,1] as shown in Figure 8(a) and 8(b) [13].



(a) (b)

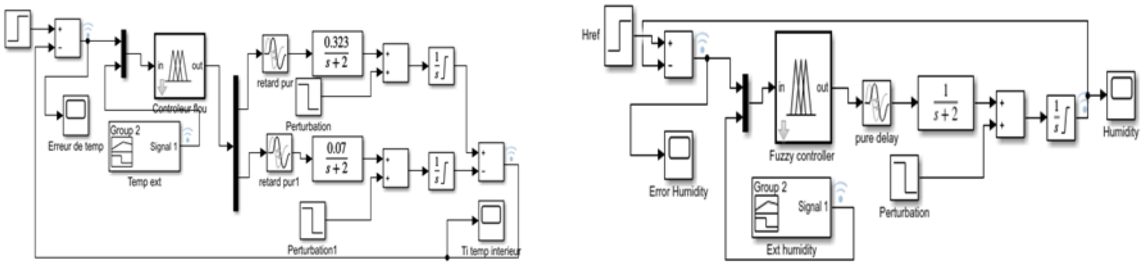
Figure 8. Fuzzy charger battery; (a) schema of charging and discharging the battery, (b) the fuzzy battery regulator model

b. Verification of the operation of the GPV generator

After confirming the robustness of the two previous controllers, we tested the operation of the GPV.

1) Optimization of the consumption of electrical energy

When the internal climate of the building is unstable, this has a great influence on the life of the hens with consequences on the consumption of electrical energy. However, to stabilize the internal climate and reduce the operating time of the equipment, thus saving energy [27], [28]. We equipped the building with two fuzzy logic controllers, temperature and humidity. The temperature controller model has two inputs, a temperature error (Tref-Ti) and external temperature T_0. Thus, it contains two outputs, to control heating and ventilation as shown in Figure 9(a). The humidity controller model has two inputs, humidity error (Href-Hi) and outdoor humidity H_0, as well as an output for controlling the humidifier as shown in Figure 9(b).



(a) (b)

Figure 9. Fuzzy logic controllers (a) The temperature controller, (b) The humidity controller

3. RESULTS

3.1. The results of the first phase

The results of the calculations of the first phase of the photovoltaic installation are summarized in Table 2. The results obtained show that the generator works correctly to meet the load demanded by the campus, because we based our calculations on the sunshine of the most devourable month.

Table 2. The dimensions of the photovoltaic power plant designed

Parameters	Dimensions
Ezone (containing two buildings)	105.15 kWh
The peak power of the panels of zone	77.88 kW
Installed power (kWp)	79.3 kW
Panel power in STD (Wc)	305 W
Total number of panels	260
Number of panels per branch/string	5/52
Parallel branches (string)	26x2
Panel efficiency under STD (%)	18.1
The DC/DC converters	100 kW,300 V, 500 V
Energie storage C_{nom}	323538.46 Wh
Total number of batteries (1 KWh, 12 V)	336 unités
DC bus voltage	500 V,
Total number of series/parallel batteries	42/8
The DC rated inverter	100 kW,800 V, 210 A
The AC rated inverter	100 kW,400 V, 146 A, 50 Hz
Rendement max.	96,40%

3.2. Résults of Second phase: verification of the feasibility of the design with the "Homer" design software

3.2.1. Global solar energy

Figure 10 obtained by the Homer software shows the significant influence of the inclination of the panels (40% additional energy for the unfavorable months). Thus, in spite of the distinctions between seasons, the annual energy produced by the inclined panels remains uniformly distributed. On the contrary, without tilting the overall solar energy is very important, but with an uneven annual distribution.

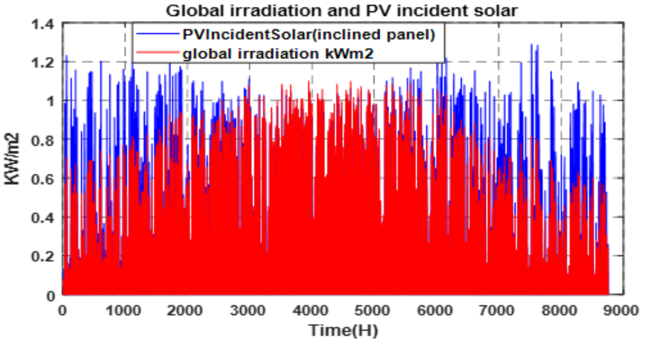
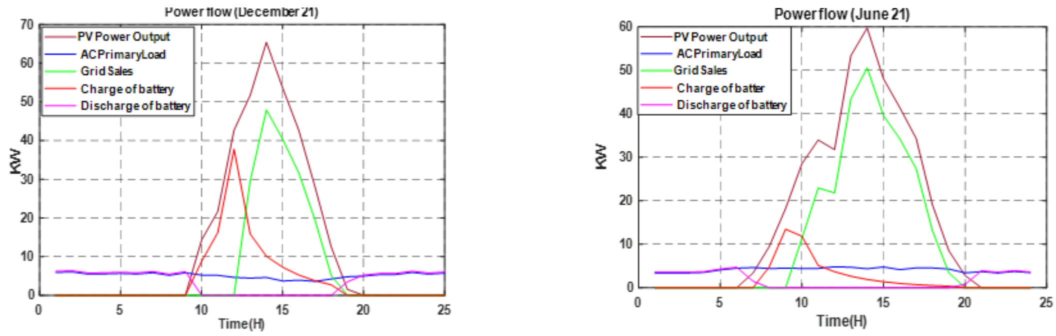


Figure 10. Annual distribution of global solar energy and energy produced by the inclined plane

3.2.2. The power flow during the summer and winter

The comparison of the production of the designed photovoltaic field with the actual consumption of the buildings during the summer solstice (June 21) and the winter solstice (December 21) obtained by Homer in Figure 11 shows that the energy demand is entirely provided by the photovoltaic generators and storage system. It is clear that in the absence of lighting, the load is met by the storage. But from sunrise onwards, the energy flow changes direction. Therefore, during the day, the increasing photovoltaic energy production can only satisfy the demand of the building and the charge of the batteries. Therefore, the company cannot sell excess energy to the power grid until the batteries are fully charged. Figures 11(a) and 11(b) show the electrical power produced by the GPV, the amount of excess electrical power sold to the grid, the charge consumption in KW and the charge/discharge of the batteries in KW.

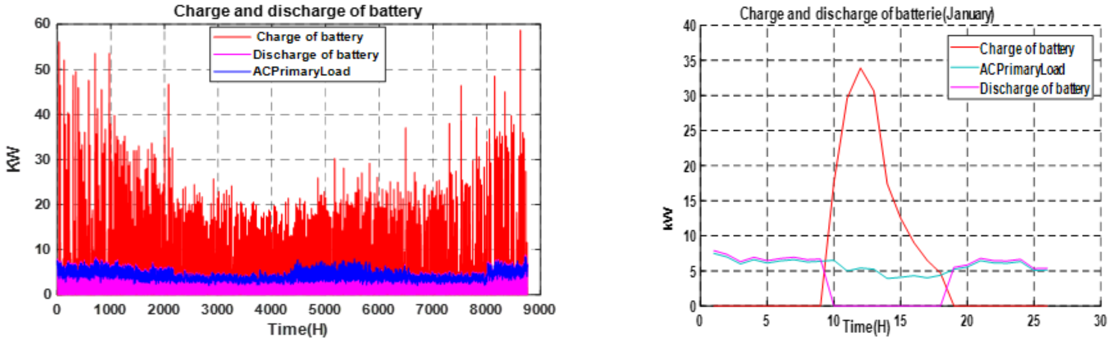


(a) (b)

Figure 11. Electrical power produced by the GPV; (a) The power flow on a winter, (b) The power flow on a summer

3.2.3. Energy storage

The Figures 12(a) and 12(b) show that the availability of energy stored by the battery fully covers the company's consumption during the night and during climatic disturbances. Indeed, this result gives us a good indicator of storage sizing, and it confirms the calculation of the capacity realized in the first phase.

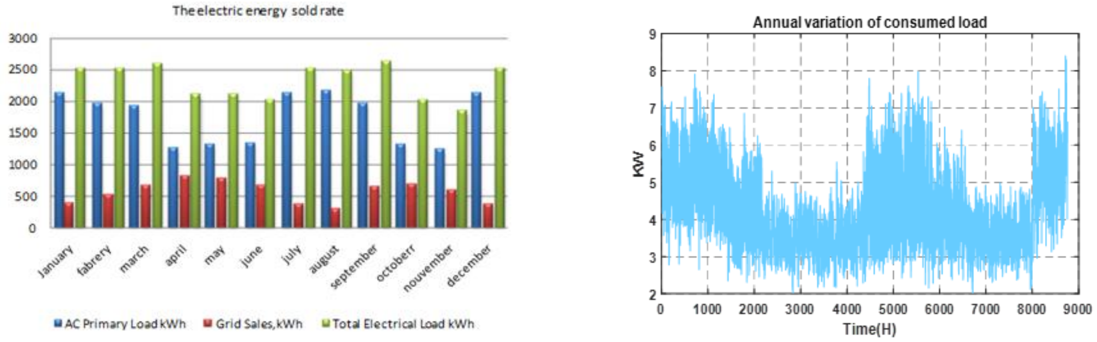


(a) (b)

Figure 12. The charge and discharge of the batteries; (a) The state of charge and discharge of the batteries for one year, (b) The charge and discharge cycle of batteries for one day

3.2.4. Evaluation

According to the histogram presented in Figure 11, the breeding center will make an additional profit each month through the sale of excess electricity to the network. We see that the energy injected into the electrical network varies according to the season and weather conditions. Furthermore, it should be noted that the total annual sales made by the company is 6,969 kWh, approximately 24.93% for an annual production of 27,959 kWh. The company consumes a total of 20,990 kWh which represents 75.07%. The load profile illustrated in Figures 13(a) and 13(b) correctly reflects the energy consumption of the farm. It is very important during temperate times, due to the air-conditioning of buildings, and it is less important during moderate seasons. Indeed, the results of the HOMER software allowed us to validate the sizing steps previously carried out and to have an optimal configuration of the system to ensure the best compromise of technical feasibility and economic profitability. In general, this study highlights the existence of a strong coupling between the components of the photovoltaic system: solar potential, structure, storage, converters, energy management and the load. Therefore, this also justifies a systematic approach to design in which energy optimization of all subsystems is necessary.



(a) (b)

Figure 13. Evaluation; (a) the energy benefit, (b) annual load

3.3. Results of the third phase

3.3.1. Optimization of the production of GPV by intelligent regulation

a. MPPT Controller tests

The graphs in Figure 14 illustrate the input and output signals of the fuzzy controller compared to the conventional P&O controller (disturbance and observation). These graphs show additional gains, power (GPV) and voltage when using the fuzzy controller, especially for transient operation, in constant weather conditions. The results show the effectiveness of the fuzzy controller. It indicates a good indication on the functioning of the designed GPV. Transient response times are very acceptable because the maximum power is reached in 0.1 s. Once again, to validate our method, we tested our controller for different irradiation and temperature values Figure 14(c).

The simulation results obtained in Figure 14(c) show again the efficiency and robustness of the fuzzy controller to extract the maximum power from the photovoltaic generator, whatever the irradiation variations (79.04 kW for 1000 W/m² and 60 kW for 800 W/m²). These results are acceptable in terms of system stability. By comparing these results, we can see that the performances of the fuzzy regulation are better than those of the "P&O" regulation. Therefore, it is proven that the fuzzy controller has better performance, fast response time, very low steady state error and robustness to different variations in atmospheric conditions.

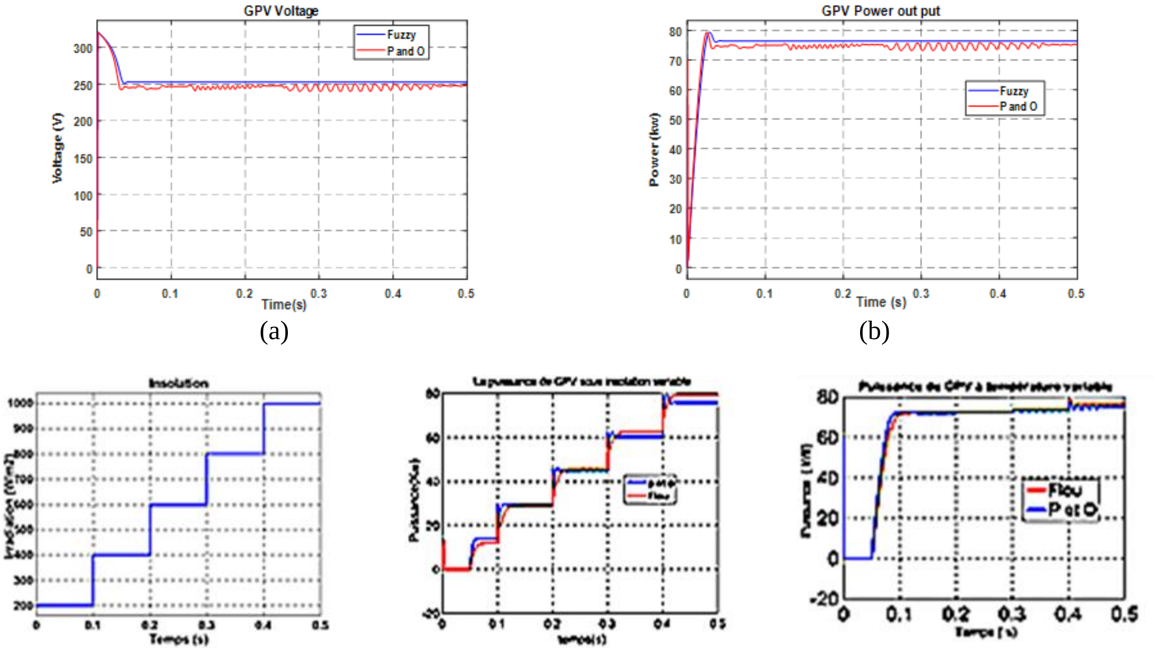
b. Results of Fuzzy charger battery test

When the irradiation changes, the voltage supplied to the load with the fuzzy controller varies in a range between 503.8 V and 504.6 V and reaches a value of 589.5 when the battery operates without regulation as shown in Figure 15. It can be concluded from this result that the influence of the voltage regulator load is maximal because it maintains the voltage in the range that protects the battery.

c. The GPV operating

On the basis of the results of the two regulators, we performed an analysis of the operation by simulating the voltage and power delivered to the load under constant irradiation and temperature conditions (1000 W/m^2, 25°) by the optimized GPV. The purpose of this simulation is to test the robustness of the fuzzy regulators and to ensure the production of the optimal system.

The results shown in Figures 16(a) and 16(b) are very acceptable. In stable mode, the frequency of 50 HZ is respected; the effective amplitude is 380 V between phases and an effective current of 120 A. The waveforms are perfectly sinusoidal after adjusting the connection filter. The transient active power reaches the value of 170 kW, which is the sum of two powers (PV generator+battery) before the intervention of the battery controller. The same behavior is observed with the effective current value of 260 A. This confirms the efficiency and superiority of the selected fuzzy controller, as well as optimal operation of the GPV.



(a)

(b)

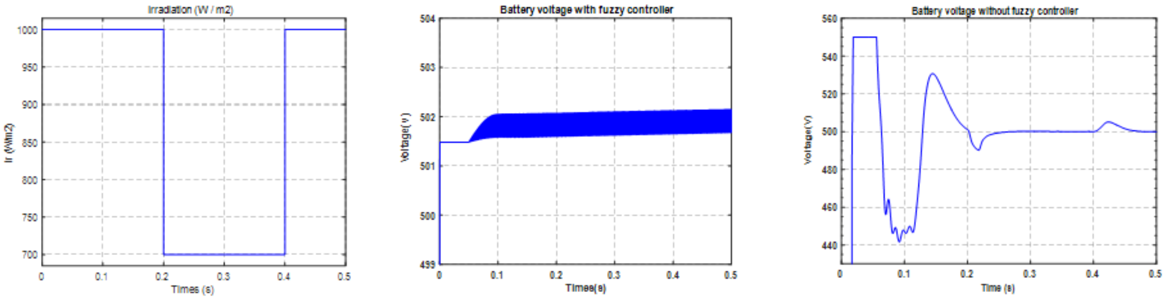
irradiation

GPV power under variable irradiation

(c)

GPV power under variable temperature

Figure 14. MPPT controller tests; (a) GPV voltage fuzzy MPPT and P&O, (b) the power of GPV Fuzzy MPPT and P&O, (c) simulation results of (boost) with fuzzy MPPT for different irradiation and temperature values

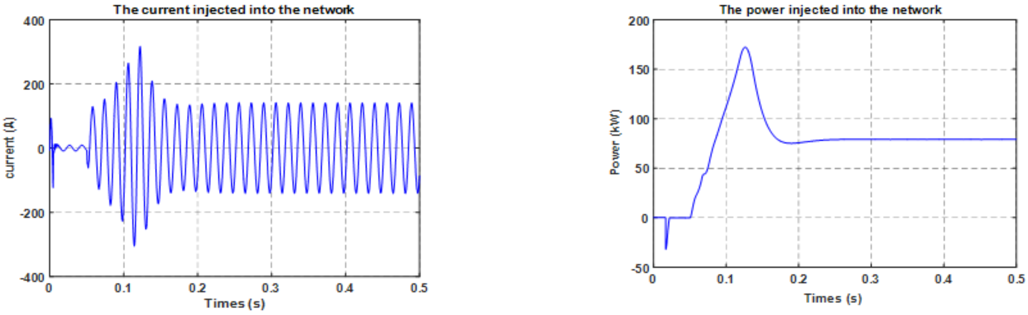


(a)

(b)

(c)

Figure 15. Simulation results (fuzzy battery charger); (a) irradiation, (b) battery voltage with fuzzy control battery, (c) voltage regulation without control



(a)

(b)

Figure 16. Simulation results; (a) current at load output, (b) power at load output

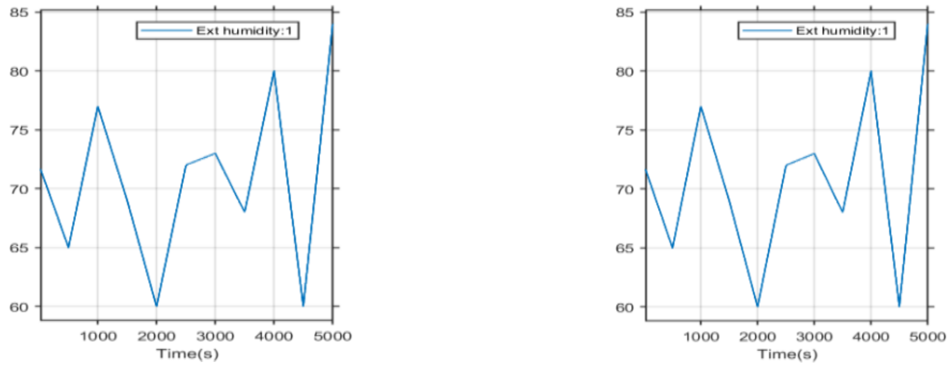
3.3.2. Results of optimization of electrical energy consumption by intelligent control of the interior climate of the livestock building

a. External disturbances in temperature and humidity

The Figure 17 shows the curves of two external disturbances in temperature and humidity respectively. These disturbances can be explained by the error between the reference and the controlled temperature value (Tref-Ti) as well as by the humidity curve (Href-Hi). We chose a step of 500 s (≈9 minutes), because the temperature and humidity variations Ti and Hi are actually quite slow. Thus at 1000 s for an outdoor temperature and humidity of 19.2 °C and 77%, the errors with reference to 25 °C and 60% are 2.4 °C for temperature and 5% for humidity. So, these results show that the internal climate is very well stabilized with the two fuzzy controllers.

b. The temperature and humidity inside the barn

The Figure 18 shows the temperature and humidity results inside the barn. We find that, without a regulator, the response would not only be slow, but also too high, which would have a harmful effect on the hens (health and nutrition), consequently on the weight of the eggs and on the yield of the laying in general. Regarding the two parameters, the effect of our regulator is fairly rapid and responds correctly to the set point. Finally, we deduced by these two tests shown in Figure 17 and Figure 18 that these regulators significantly improve the system by reducing the equipment operating time. Consequently, we have noticed a remarkable optimization of the energy consumed by the building.



External humidity External temperature

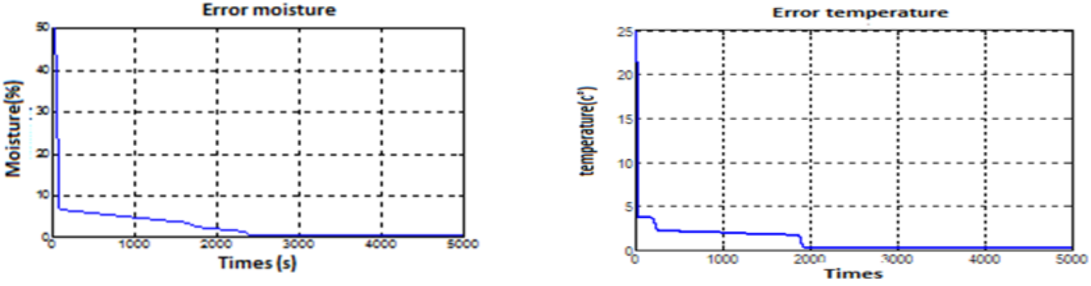


Figure 17. Inputs of the fuzzy controllers

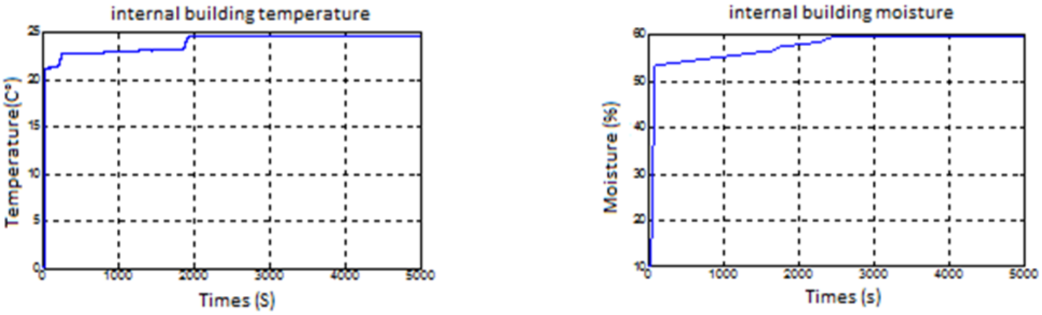


Figure 18. Internal temperature and humidity (controlled)

4. CONCLUSION

In this work, we presented a methodology for the design of an intelligent photovoltaic power plant connected to the grid with storage to feed a chicken breeding company. This approach facilitates the integration of renewable energies in agriculture and reduces the consumption of fossil fuels. These photovoltaic systems make a significant contribution to relieving the burden on the national electricity grid and provide a better service to farmers. In addition to helping to reduce the effects of carbon dioxide, the intelligent power plant also improves the quality of service (no disruption to the power grid). It will benefit from 24.93% of the sale of surplus energy to the national grid. This is mainly due to the optimization of energy production and consumption by fuzzy controllers.

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