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DEVELOPMENT AND INTEGRATION OF PHOTOVOLTAIC COMPLEX SYSTEMS IN OPTOELECTRONIC AND POWER APPLICATIONS

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Abstract: *This thesis presented innovative dimensioning and implementation of autonomous photovoltaic systems is primarily aimed at ensuring the energy independence of the receiver (consumer), the security of electricity supply and the adaptation to meteorological conditions in the area where they are located. The PV system components are based on literature, but their characterization was possible by implementing the components / system in the MATLAB / Simulink work environment to determine the behavior and performance of the analyzed system for different applications. We also analyzed the interdependence of the subsystems and how they affect the efficiency of the PV system. The main contribution of this paper is based on MPPT method and FLC controller used in order to optimize the behavior of applied PV systems.*

Keywords: Optimized PV system, application, simulation, modeling, software tools, MPPT, FLC

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1. Introduction

1.1 Photovoltaic technology

The solar cell represents the fundamental unity of the PV system. The photovoltaic module is the solar cell matrix. The specific parameters of photovoltaic module are: 1) open circuit voltage (Voc), 2) short circuit current (Isc), and 3) FFM module fill factor. The power generated by PV modules in real-world applications can range from 20 to 60 Wp or 300-350 Wp depending on panel size and technology.

The BOS system represents all the photovoltaic components with conversion (inverter), stabilization (electrical regulator) and electrical energy storage (battery).

The DC-AC inverter or converter is a BOS element that is particularly important for photovoltaic systems, especially for PV-integrated PV systems, but also for stand-alone PV systems. In the case of PV-connected PV systems, the inverter faces more delicate tasks due to the fluctuating power of photovoltaic modules. As a result, the inverter has an essential role (in addition to the DC to AC conversion) to stabilize the voltage and THD (Total Harmonics Distortions), respectively.

The DC-DC converter (regulator) also called DC voltage regulator can be defined as a device to convert DC power with constant parameters.

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The electrical storage system is a vital component of the photovoltaic system. Energy storage is very important, both on a small scale and on a large scale, to cope with the variation in energy production from renewable sources.

1.2 Typologies of applications of photovoltaic systems

A. Applications of autonomous PV systems

Autonomous PV systems operate without the use of other power sources. Two applications studied in the PhD thesis were represented by solar pumping and photovoltaic lighting. Solar irrigation systems are used in areas with high solar potential and where there is no possibility of using other sources of energy, including the connection to the grid. Photovoltaic lighting is an effective way of implementing energy-efficient solutions, both in terms of technology used and power consumption.

B. Applications of integrated PV systems (distributed generation)

The integration of photovoltaic systems into buildings in the context of the new concept nZEB (nearly zero energy building) is a challenge both for building energy independence of buildings and for correlating them with the specific architectural style of existing buildings. These systems can generate the electrical energy required for the building's load on the integrated grid operation; these units behave as an additional source of energy that reduces the costs associated with electricity consumption in the distribution grid.

2. State of the art to development of PV systems

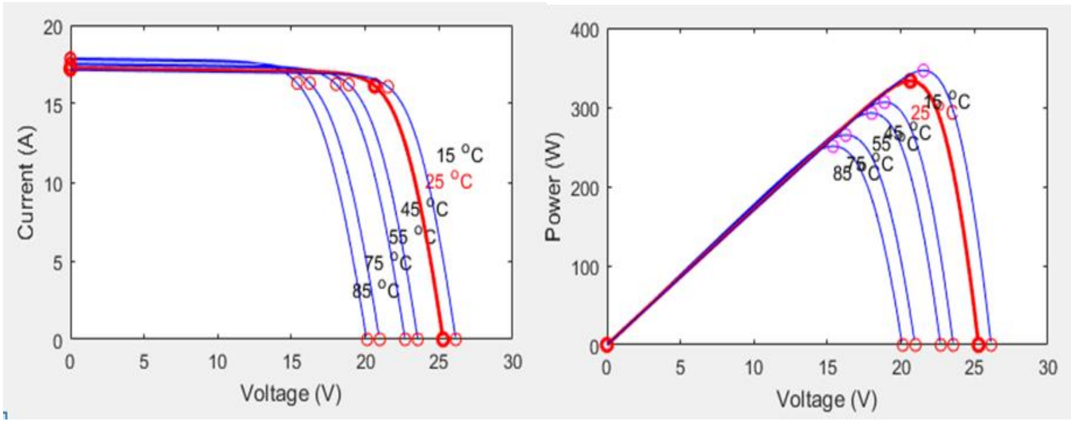
The annual growth of the photovoltaic industry is mainly driven by major investment and political support both in developed countries such as Germany, Norway and in less developed countries in Europe or other continents. These major investments in the photovoltaic industry have made possible to increase the conversion efficiency to about 46% for "multi junction" solar cells, this value being reported by the German research institute Fraunhofer. Also, industry's desire to minimize costs per MW is driving the development of new technologies, materials and new solutions to improve solar energy conversion efficiency. At the same time, investments in renewable energy become more advantageous because the global supply of fossil fuel starts to lose ground in the face of green energies. The correlation of well-known and established techniques with new concepts is a good way to improve the current solar cell without the need to revolutionize the existing industry. Silicon solar cells, today's standard, can be used as the basis for the next generation of solar cells in the mass. The value of the renewable energy market amounts to 2017 (according to Fraunhofer report) at 1.75 GW for Germany, 8.6 GW for European Union and 94.6 GW globally.

3. Analysis, simulation and optimization of PV systems

3.1 Numerical Modeling and Simulation of Photovoltaic Systems

3.1.1 Evaluation of the characteristics and performance of the numerical modeling of a PV generator.

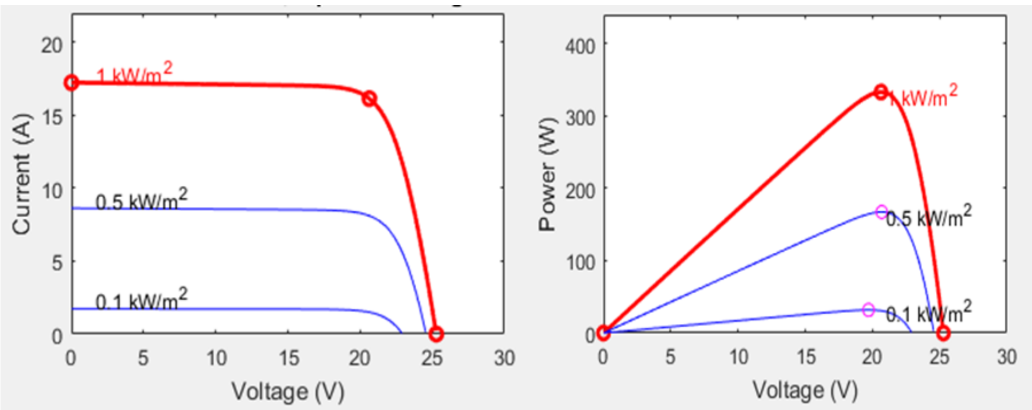
The technical parameters of the PV module of the photovoltaic system components were obtained from the Suntech manufacturer's catalog. In order to model and simulate the electrical performances of the PV generator, they used the Simulink / MATLAB module library for its implementation and testing. The characteristics and performance of the photovoltaic generator have been analyzed for a temperature range of 15-85 ˚C in Figures 3.1a and 3.1b. At the same time, the characteristics and performances of the photovoltaic generator were also analyzed in terms of solar radiation values in the range 100-1000 W / m2 in Figures 3.2a and 3.2b.



a) *I-V (current-voltage) in PV generator analysis for different temperature values*

b) *P-V (power-voltage) in PV generator analysis for different temperature values*

Fig. 3.1*: I-V (current-voltage) and P-V (power-voltage) in PV generator analysis for different temperature values*

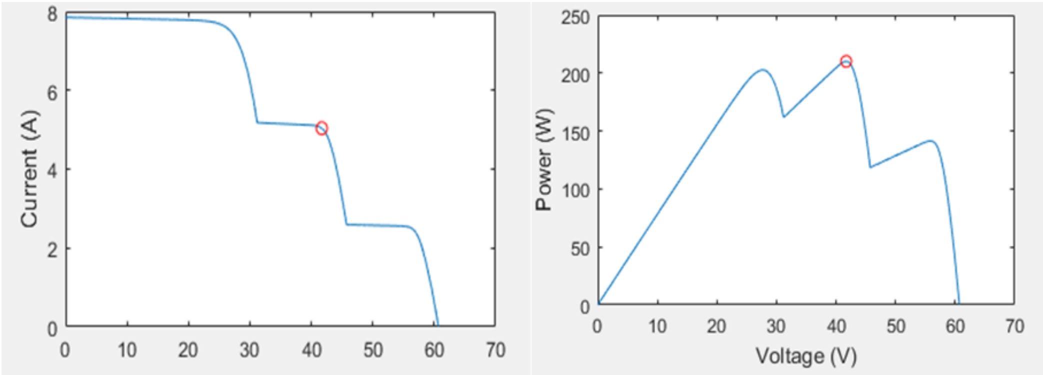


a) *I-V (current-voltage) for different values of solar irradiation*

b) *P-V (power-voltage) for different values of solar irradiation*

Fig. 3.2 *I-V (current-voltage) and P-V (power-voltage) in the analysis of the PV generator for different values of solar irradiation*

Based on the results obtained from the I-V and P-V characterization we obtained the maximum power developed by the photovoltaic panel (about 210 W), the maximum voltage (about 42 V) and the maximum current through it (about 5 A). The results are presented in Figure 3.3.



a) Maximum current for a 42 V voltage b) Maximum power developed by the panel

Fig. 3.3 *Maximum performance recorded by the photovoltaic panel considered*

3.1.2 Performance evaluation of the numerical modeling storage system. Obtained results

An important element of the stand-alone PV system is the storage system. The battery is required in such a system to reduce the fluctuations of the energy delivered by the photovoltaic generator to the load. In Figure 3.4 and 3.5 the voltage behavior was determined in two different modes of operation.

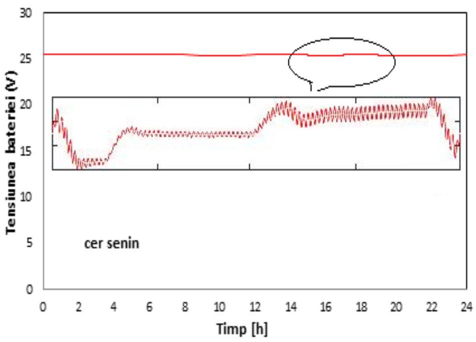


Fig. 3.4 *Behavior of battery voltage during a clear day*

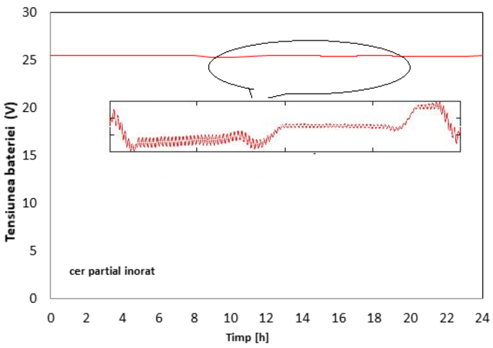


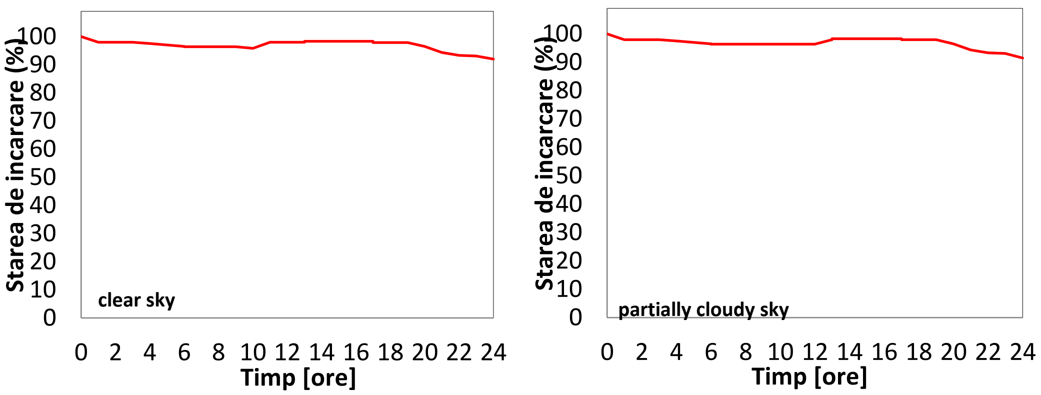
Fig. 3.5 *Behavior of battery voltage during a cloudy day*

3.1.3 Performance analysis of the DC / DC converter (controller) by numerical modeling. Obtained results

The DC / DC controller of the photovoltaic system requires all electrical storage and power systems to include a control strategy that describes the interactions between its components. Using the battery as a storage device involves the presence of a charging regulator. This device is used to manage the energy flow of the photovoltaic generator, battery, and load by collecting battery voltage information and indicating its maximum and minimum acceptable values.

The performance of the controller is analyzed using the MATLAB / Simulink software.

In Figure 3.6, a & b shows the charging state of the autonomous PV system battery under the direct supervision of the controller, it is noted that the battery is correctly charged for the both cases (sunny day / partially cloudy day).

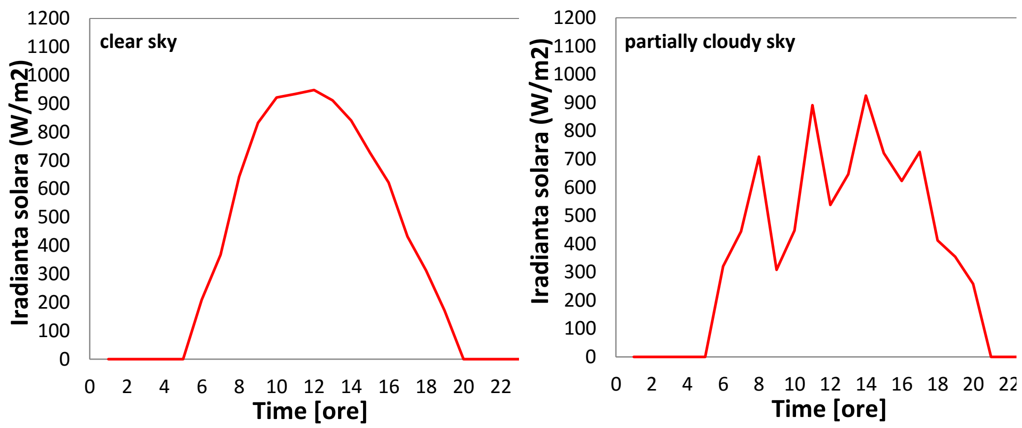


a) b)

Fig. 3.6 (a & b): *Battery charging state of the stand-alone photovoltaic system based on controller monitoring*

3.1.4 Modeling and numerical simulation of the PV system. Obtained results and achieved performances

Figure 3.7 (a & b) presents the one-day evolution of a solar irradiation level for two cases, namely: 1) a day with clear sky, and 2) a partly cloudy day. Based on these diagrams, a global analysis of the photovoltaic system can be considered to determine the behavior and performance of the system.

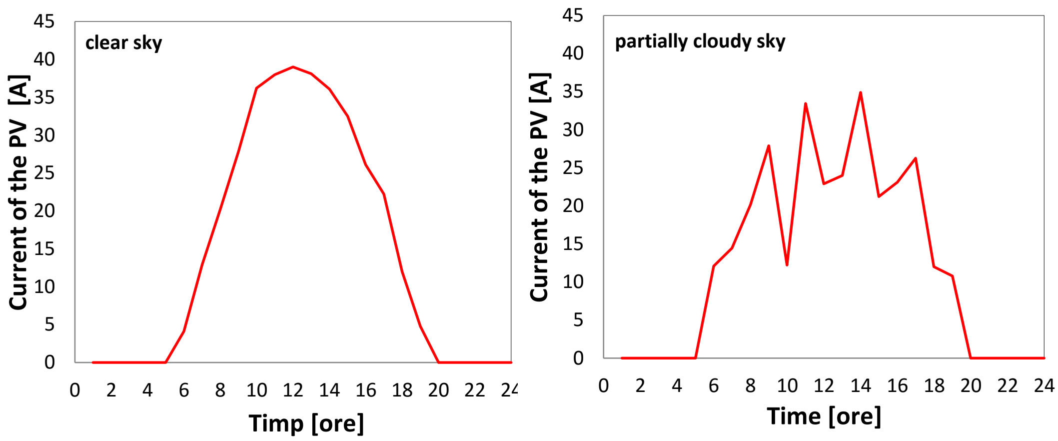


a) b)

Fig. 3.7 (a & b): *Evolution of solar irradiation over a day with clear / partly cloudy sky for standard test conditions (STC)*

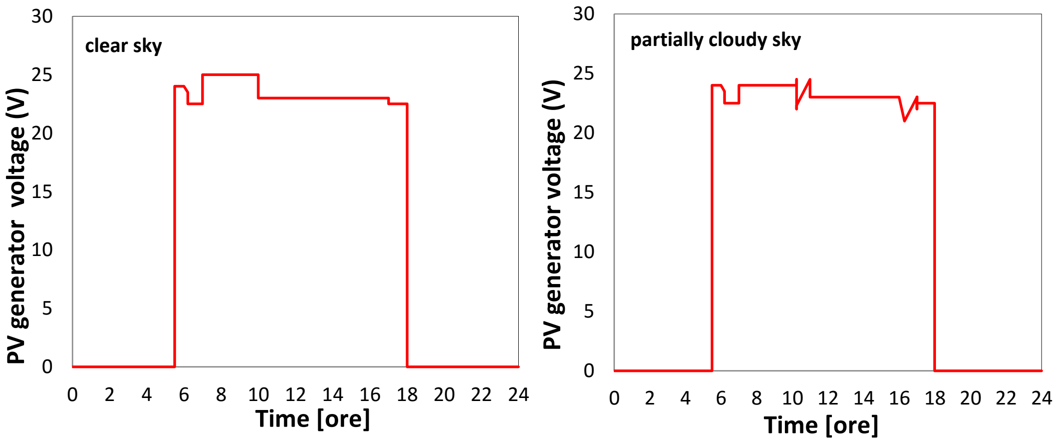
Using the Simulink software and the approach of two types of days, we obtained the current evolution for the photovoltaic generator (Fig 3.7 a & b).
On a partially cloudy day, we can observe strong fluctuations in the current provided by the photovoltaic generator; they can affect battery charge and operation (see Fig. 3.8 a & b.) Also, the

voltage of the PV generator and the load voltage of the photovoltaic system have comparable values for the both analyzed cases: a clear day and a partly cloudy day (see Fig. 3.9 a & b and Fig. 3.10 a & b). At the same time, it is noted that the voltage is less influenced by the fluctuations of solar irradiation.
The considered photovoltaic generator provides voltage only during the day, between 08: 00-20: 00, and the photovoltaic system load voltage is approximately constant throughout the day-night cycle.



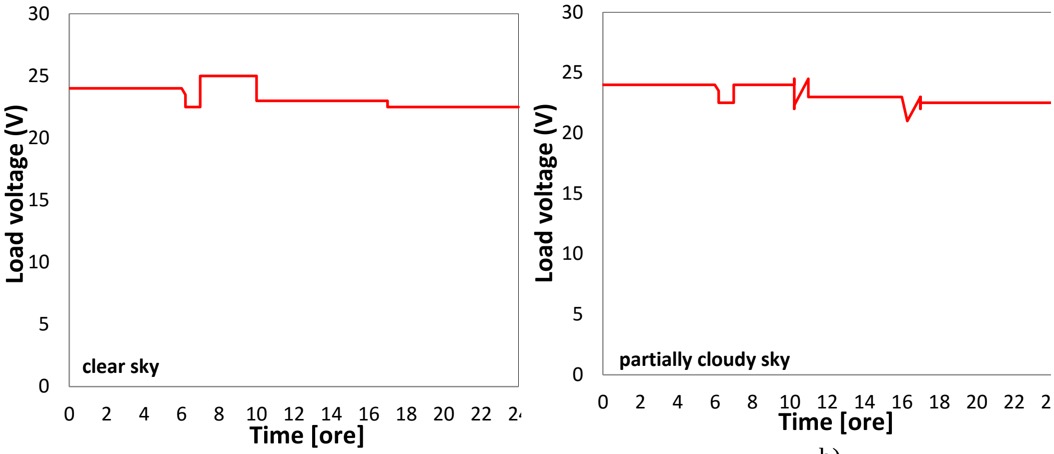
a) b)

Fig. 3.8 *The daily evolution of the current for photovoltaic generator*



a) b)

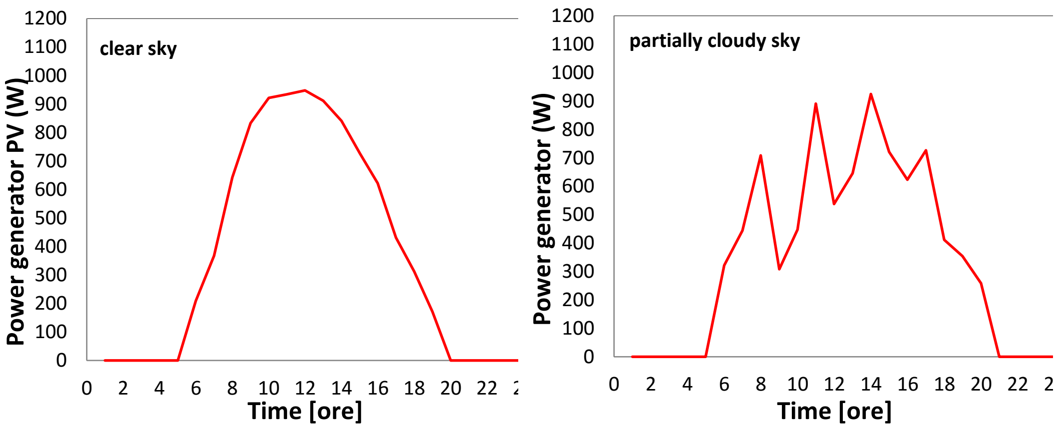
Fig. 3.9 *The daily evolution of the voltage for the photovoltaic generator*



a) b)

Fig. 3.10 *The daily evolution of the charge voltage for the photovoltaic system*

The evolution of daytime power for the PV system in the case of a clear sky day or a partially cloudy day is indicated in figure 3.11 a & b. The PV curve evolution curves during the test day tend to the trend curves solar irradiation corresponding to the day considered. The evolution of daytime battery power for the PV system during the day-night cycle (Fig. 3.12 a & b) depends on the corresponding solar irradiation level; so unlike the days with clear sky, for partially shaded days, the battery's power the day's evolution is badly affected. Also, daytime battery power is influenced by the consumer's load in the both situations: sunny day and partially sunny day (Fig. 3.13a & b).



a) b)

Fig. 3.11 *The daily evolution of power for the photovoltaic generator*

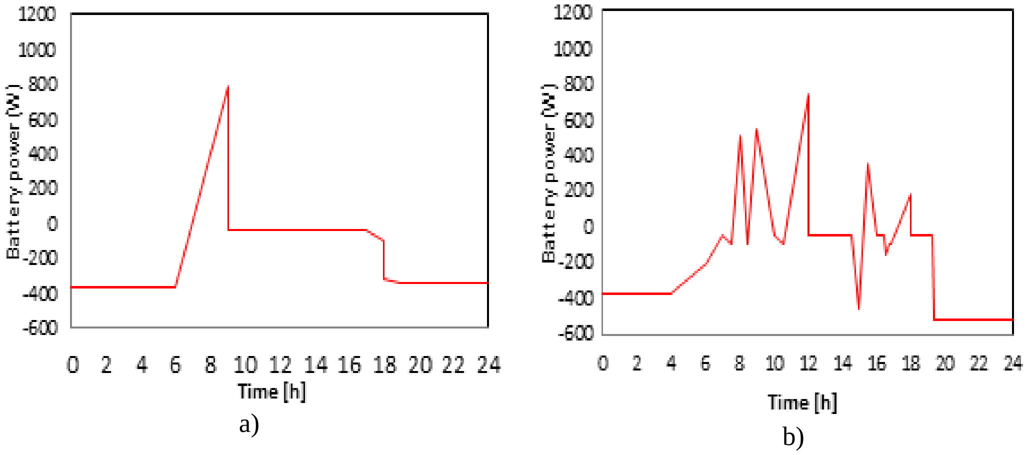


Fig. 3.12 *The daily evolution of battery power for the photovoltaic system*

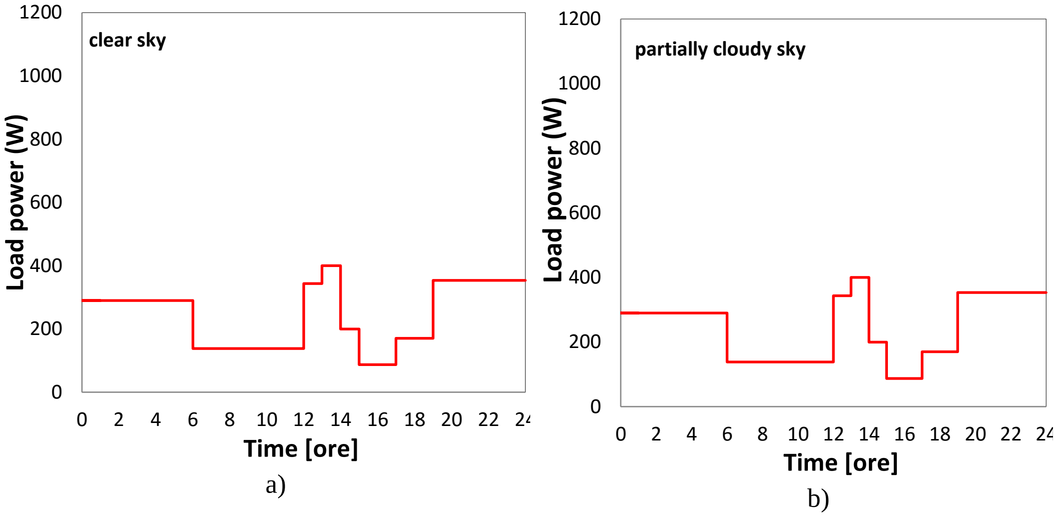


Fig. 3.13 The daily evolution of the charge power for the photovoltaic system

3.2 Improving the performance of PV systems by MPPT technique and FLC algorithms

3.2.1 Implementation of the MPLC based FLC algorithm and PV simulation and modeling

A) The FLC based controller implemented in the PV system configuration

Maximum power point tracking is implemented using an incremental algorithm and a fuzzy logic controller. The incremental algorithm compares the true power of the PV system (PPV) with an estimated maximum power (reference power) (Pr) through the FLC controller at equal time intervals. The output of the FLC controller is used to direct the reference power to a new level, which is added to the previous value of each range. The highest power value can be considered as the maximum power. The output signal from the FLC controller is directed to a PWM to control the operation cycle of the DC-DC voltage converter. The DC-DC converter raises the voltage to the value at which the PV system can operate at full power. Fig 3.14 shows the configuration of the MPPT - FLC controller.

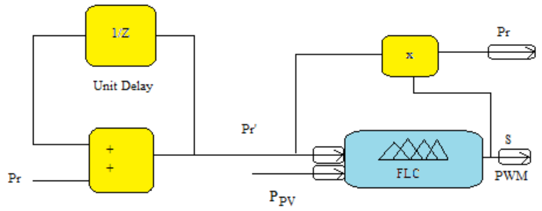


***Fig. 3.14 MPPT** Configuration of the MPPT - FLC controller*

B) The studied FLC controller implemented in the battery controller configuration

Battery charging operations and power transfer occur under fast variations. For this reason, it can be said that the battery controller control operation is essential for the efficiency and stability of the PV system. The battery operation to control total power distribution and load and discharge load operation with the FLC control algorithm can be described by the following modes: 1) Charge mode, 2) Discharge mode, and 3) Standby mode:
Fig. 3.15 shows the configuration of the FLC controller:

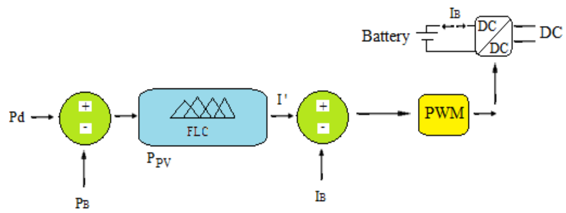


***Fig. 3.15** Battery control units*

C) The studied FLC controller implemented in the electrical consumer voltage configuration

In any load specification there are certain current / voltage values, respectively the power to be supplied correctly to the load during the operation of the complex PV system. The control of voltage and load current is done by implementing a MPLC-based FLC algorithm in the Matlab / Simulink work environment for power control.
Using the control method used, the voltage, current and output power are adjusted and stabilized at the optimum load value. Figure 3.16 shows the load controller configuration.

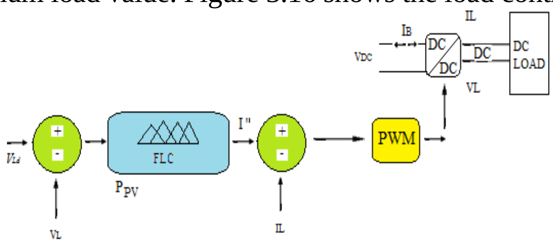


***Fig. 3.16 Load** controller scheme*

3.2.2 Interpretation of the results obtained in numerical modeling and numerical simulation of the PV system by using FLC and MPPT

Simulations obtained with the Matlab software and the MPPT and FLC algorithms have yielded interesting results on the behavior, stability and performance of the complex PV system studied. Fig. 3.17 (a, b, c, d) shows the behavior of the voltage through the components of the complex PV system. In Fig. 3.17 (a) it can be seen that the voltage of the PV generator shows fluctuations, with a sharp drop after about 20 seconds. In Fig. 3.17(b) it can see that the load voltage is stabilized around 18 V after about 10 seconds. Fig. 3.18c shows that the charging voltage drives the battery to a maximum capacity of 50 V over the simulated range (60 seconds), by MPPT intervention which causes the maximum operating point to be reached (see Fig. 3.17d).

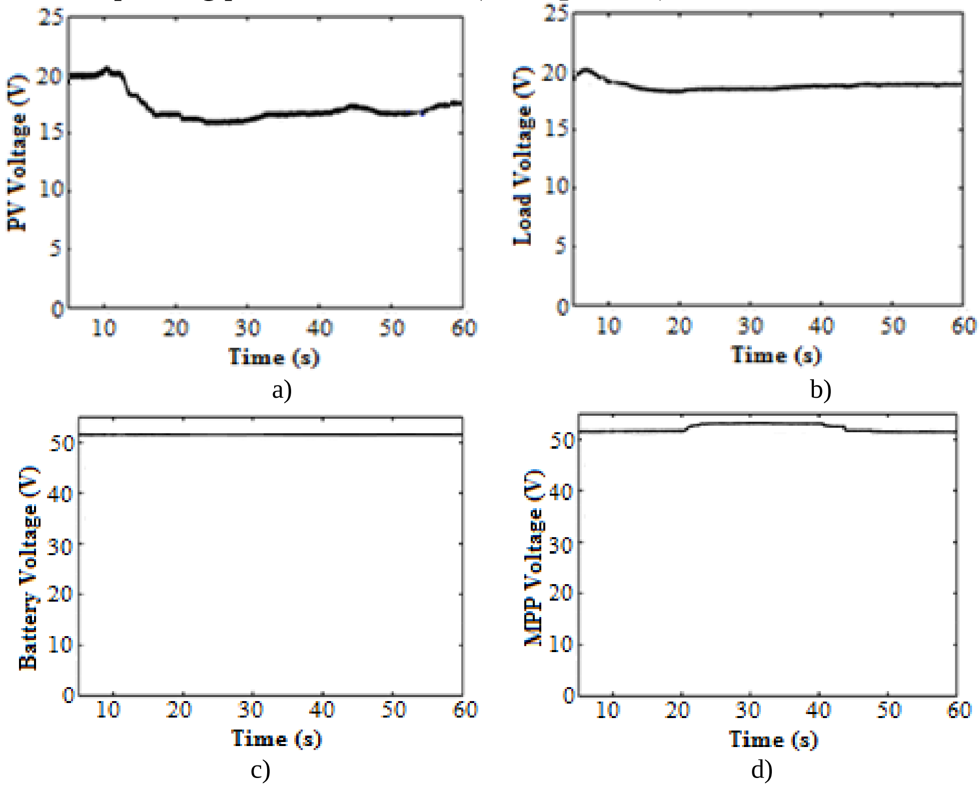


Fig. 3.17. *Voltage response in complex PV system. a) PV generator voltage; b) load voltage; c) battery voltage; d) MPPT voltage*

Fig. 3.18 a) and b) defines the voltage and current response for the three components of the complex PV system. In this way, both voltage and current developments can be simultaneously viewed, which allows an understanding of the behavior on different segments of the complex PV system, both from the consumer point of view and the stability of the system.

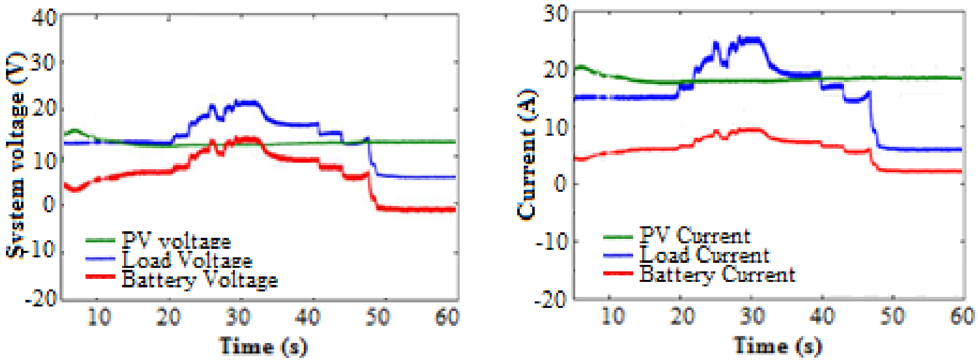


***Fig. 3.18** Current and voltage behavior over time for different input and output parameters of the photovoltaic system (solar irradiation, load, battery voltage)*

3.2.3 Numerical modeling of the complex PV system for a specific application. Results and performance achieved

The performance and results of the PV system, analyzed in the previous sub-chapter, aimed to determine the electrical parameters of the system, as well as its behavior under different operating conditions, in order to determine its capability and stability to cope with the rapid variation of input, and how it can satisfy the consumer's task.

The state of the photovoltaic generator structured on four PV modules with a total power of 1200 W was analyzed. Figure 3.19 shows the state of charging / discharging of the system (PV generator + electrical storage system) for three days. It is noted that the maximum operating power, determined by the MPPT by FLC, allows charging and discharging the battery without sensitive fluctuations, especially during the second day of the considered interval.

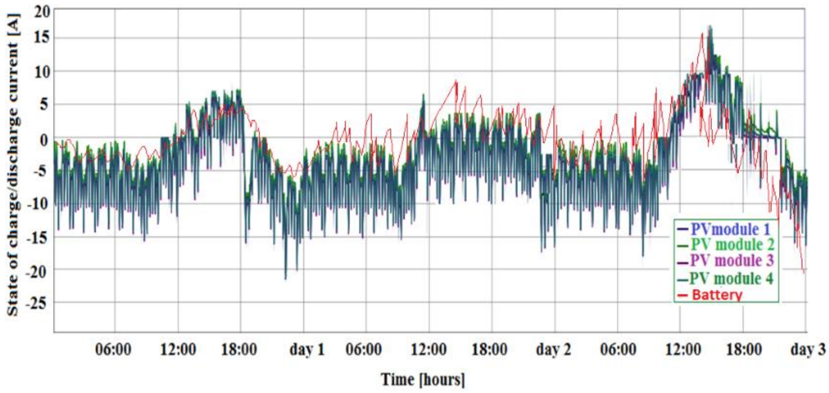


***Fig. 3.19 System** charging / discharging state (PV generator + electrical storage system)*

In order to accurately highlight the operation of the complex PV system, Fig. 3.20 shows the efficiency of the complex PV system for the time interval 6:00 - 21:00, showing the continuous behavior and functionality for both the PV generator (including the electric battery) as well as for the consumer characterized by the LED lighting system. It is noted that the efficiency of the PV system is characterized by rapid fluctuations in time the efficient use of consumer electricity is constant over the entire time interval considered. Fig. 3.21 shows the final PV system analysis over a 5-month period (long-term). Strong fluctuations in PV generator efficiency, slower fluctuations in battery efficiency, and consumer electricity efficiency constant (also determined by the use of MPPT and FLC) are highlighted.

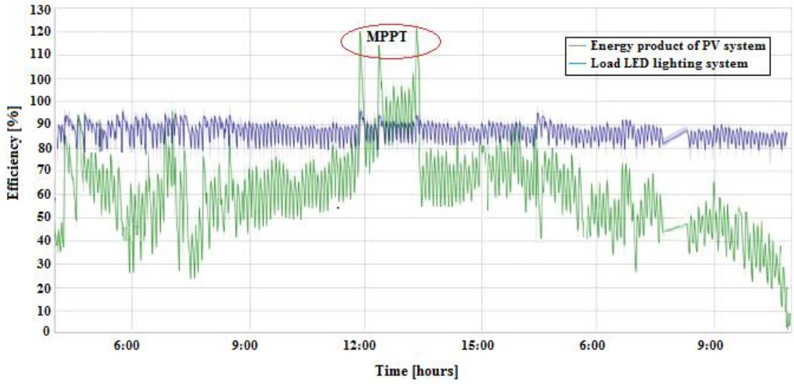


Fig. 3.20. *The medium-term efficiency of the complex PV system*

Thus, MPPT and FLC methods are very effective in both situations (both medium and long term), making it possible to determine as accurately as possible the maximum power of the complex photovoltaic system (by tracking the maximum power point) dimensioning of the system as accurate as possible, by fully satisfying the requirements of the electrical consumer (stability, continuity and electrical system parameters).

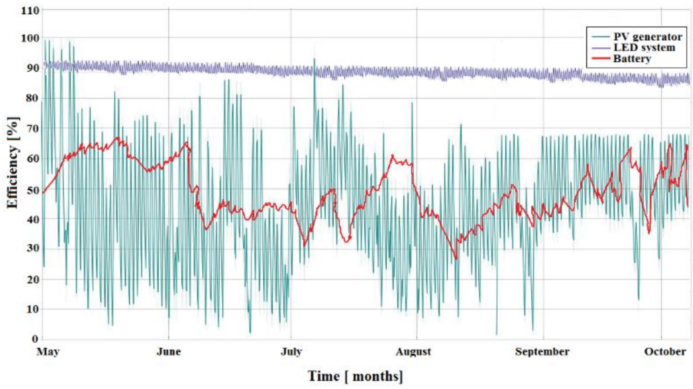
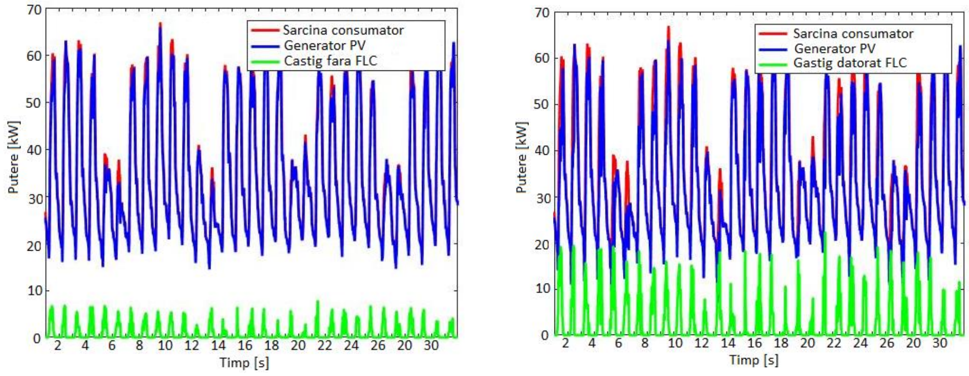


Fig. 3.21. *The long-term efficiency of the complex PV system*



a) b)

Fig. 3.22 *System power gain recorded a) with no FLC and b) with FLC*

At the same time, by optimizing the PV system by means of the MPPT technique based on the FLC controller, a significant increase in power, as represented by the variant without FLC, can be obtained (figure 3.22 a & b).

4. Contributions to the integration of photovoltaic systems in specific applications

4.1. Optimization and integration of PV systems in the building (BIPV systems)

In order to be able to use PV systems at a higher capacity, the maximum power must be extracted under the given operating conditions to increase their electrical efficiency. To achieve this, different techniques are applied, the most used and efficient method being to track the Maximum Power Point Tracking (MPPT). To improve the performance of BIPV systems a modeling and numerical simulation was developed based on the following approaches: 1) the influence of shading on the BIPV system; and 2) the application of a method based on the MPPT algorithm.

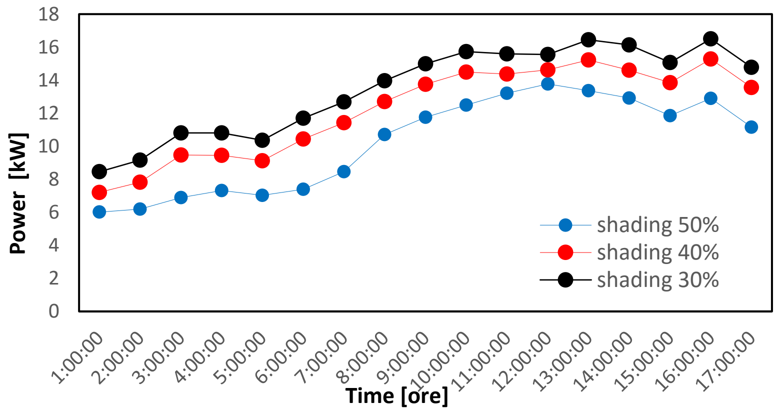


Fig. 4.1 *PV generator behavior for different degrees of shading, conventional approach*

The power of the photovoltaic generator (the total of 120 photovoltaic modules) was obtained by numerical modeling over a period of three days. The power of the studied BIPV (power generated 30 kW) has been analyzed for photovoltaic modules for different degrees of shading, namely: 50%, 40% and 30% (see Fig. 4.1). In order to determine the behavior of the BIPV system, we considered the decomposition of the PV generator function in Fig. 4.2 in three cases.

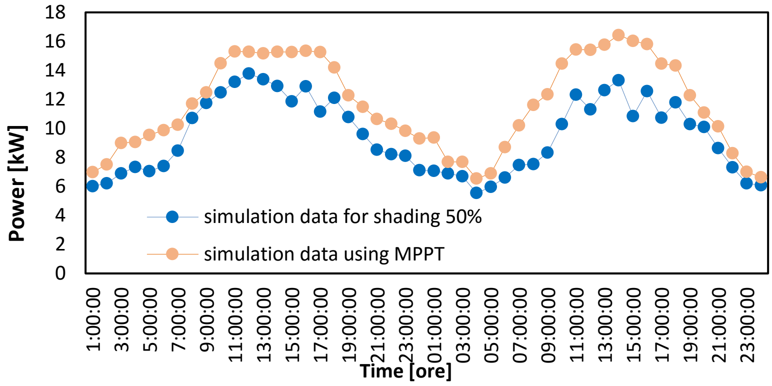


Fig. 4.2 *Power generated by BIPV for 50% shading, MPPT approach*

The power variation of the BIPV system for a shading degree of 50% is shown in Fig. 4.2. The power generated is indicated by the blue line in the case of MPPT and the orange line in the case of MPPT. There is an increase in power of 4 kW when considering the MPPT algorithm; this approach achieves an optimized power value of 16 kW.

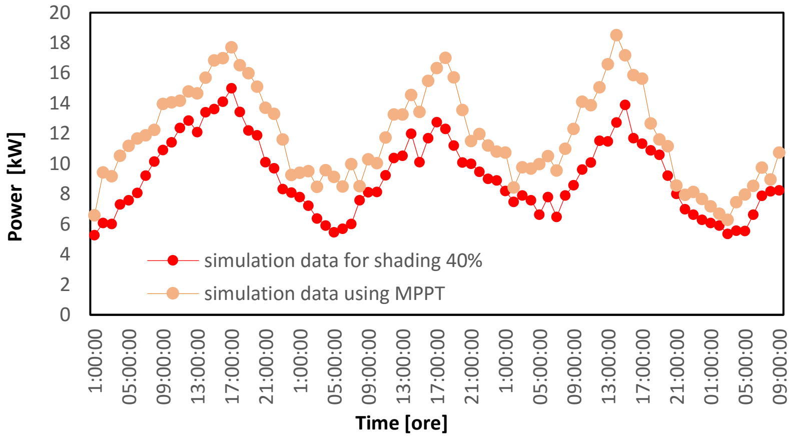


Fig. 4.3 *Power generated by BIPV for shading operation of 40%, MPPT approach*

Fig. 4.3 shows the operation of the BIPV system for a shading degree of 40%. It is noted that although the BIPV power does not exceed 19 kW compared to the proposed 30 kW, there is an improvement in MPPT operation (gain of about 6 kW) compared to the non-MPPT case. However, the shading remains a factor in reducing the effectiveness of BIPV.

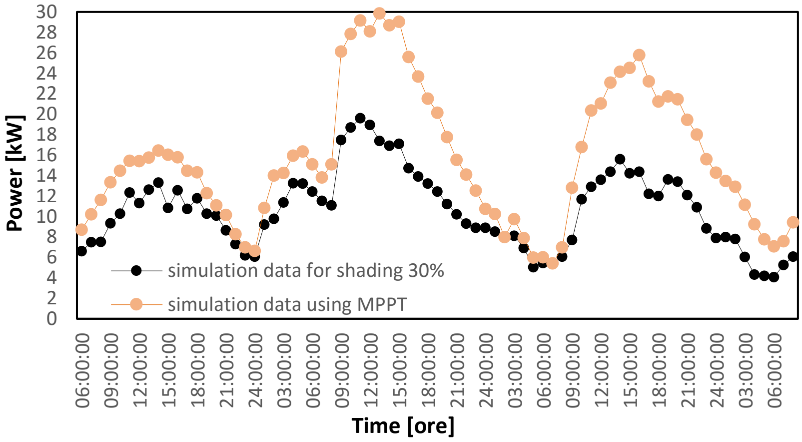


Fig. 4.4 *The power generated by BIPV for 30% shading, MPPT approach*

Fig. 4.4 presents the power generated by the BIPV system for the lowest degree of shading (30%) from the three analyzed cases. It is remarkable that the BIPV system has an important improvement for the MPPT operation - represented by the orange line. The maximum power achieved with the MPPT controller could manage and optimize the system at a power output of 29 kW, a value very close to the 30 kW target for the studied BIPV system (an increase in power of about 9 kW is achieved with MPPT). This analysis indicates a feasible approximation that could be used in pre-dimensioning a real BIPV structure.

4.2 Optimization and integration of PV systems in agricultural applications. PV pumping systems

Using the SISIFO simulation platform it would be possible to obtain the main performance of the analyzed photovoltaic pumping system. The total performance of the PV pumping system analyzed is shown in Figure 4.6. These are: monthly flow, monthly DC power to the pump motor, monthly engine power of the pump motor and monthly hydraulic energy, all related to the electricity generated by the photovoltaic generator. The maximum values of these quantities are obtained in July. All these performances define the best period of operation of the PV pumping system, namely from March to October.

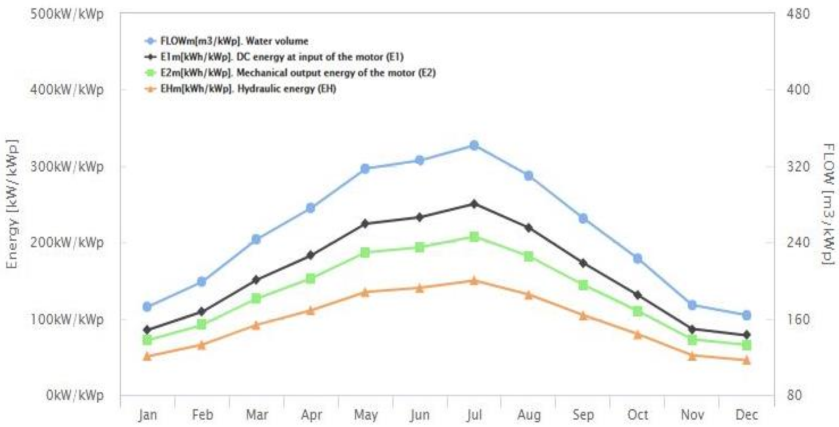


Fig. 4.6 *Overall performance of the PV pumping system*

To analyze an optimized operation of the PV pumping system, we proposed an original approach based on the MPPT algorithm and the Pulse Width Modulation (PWM) through development and implementation in MATLAB / Simulink software. We obtained the behavior of the PV pumping system for two cases, namely: 1) without the MPPT controller (disabled) (according to Fig. 4.7) and 2) with MPPT controller (activated) (see Fig. 4.8). Fig. 4.7 and Fig. 4.8 show the power output of the photovoltaic generator or the pump motor for the two mentioned cases. It is noted that: Photovoltaic generator output power fluctuations are important if the MPPT controller is not used (disabled) and are significantly reduced when using the MPPT controller (activated).

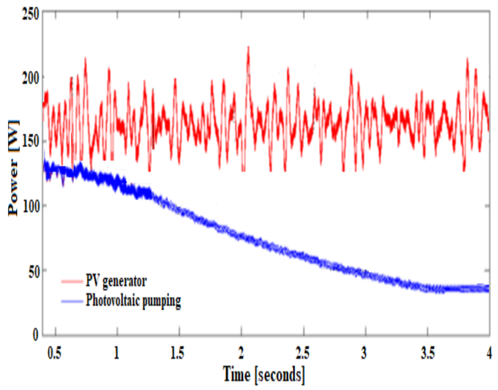


Fig. 4.7 *Performance of the PV pump with MPPT disabled*

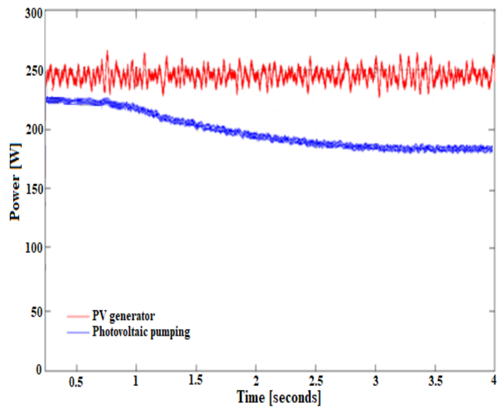


Fig. 4.8 *Performance of the PV pump with MPPT activated*

5. Conclusions

1. It was developed a modeling, simulation and optimization method for autonomous photovoltaic (PV) systems based on the Matlab / Simulink work environment. It was analyzed the interdependence of the PV subsystems and how they affect the efficiency of the electrical system. The optimization of the PV system has been achieved at important

variations of the main meteorological parameters (solar irradiation, temperature and nebulosity).
2. It was implemented an algorithm that uses the maximum point tracking technique (MPPT) by integrating a fuzzy logic controller (FLC), which has enabled the optimization of the complex photovoltaic system analyzed under different weather conditions. It was analyzed the behavior, performance and stability of the photovoltaic system on three categories of distinct time intervals, namely: short-term, medium and long-term. This approach has allowed to maximize the output power of the PV system and to reduce fluctuations in the system.
3. It was proposed an original method of optimizing BIPV systems for residential applications using a MPPT controller to improve overall performance. It was analyzed the influence of shading on the output power of the PV system. In this way we have stabilized and improved the output parameters of the PV system from the point of view of safety in the power supply of the consumer.
4. It was proposed an original method of sizing of a photovoltaic pumping system with applications for irrigation. It was developed an original optimization model for PV pumping systems based on MPPT and PWM controller and implemented in Matlab / Simulink. It was also designed an optimized PV system pump control scheme with an efficient response to sudden variations in the PV generator.

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