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Maximum Power Tracking of Photovoltaic Modules Based on Fuzzy Logic Employing Four-Phase Intervaled Boost Converter

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Abstract

Currently, there are significant investments in the study of distributed generation, including solar energy by the photovoltaic conversion method. Basically, a cell directly converts solar energy to electricity. For this, static converters are required. However, relevant issues arise in this process: point of maximum efficiency of module generation, strategy of control of the flow of energy to the network. The aim of this work is to monitor the main variables of a photovoltaic system, specifically the voltage and current module and their derivates. The goal is to implement the maximum power tracking technique using Fuzzy logic. In addition, the energy provided by the cell will be employed in an inverter stage that can operate as an active filter, voltage regulator, or generator of reactive and active power. The feasibility of using Fuzzy logic will also be studied. The first stage of this work involves parameterization and simulation of photovoltaic modules. The initial study examines the compatibility of a commercial module and its catalog data with the results of simulation. The simulated I-V characteristics show almost identical results to the catalog data. In sequence, a boost or lift DC-DC converter is employed to emulate variable load for maximum power transfer.

Keywords

Distributed Generation, Converters, Photovoltaic, Fuzzy

1. Introduction

Several Maximum Power Point Tracking (MPPT) techniques have been proposed in the literature, including perturb-and-observe, incremental conductance, and hill climbing methods. These methods have shown varying degrees of success in maximizing the power output of PV systems. However, there is a growing interest in employing fuzzy logic control techniques to enhance the performance of MPPT algorithms. Fuzzy logic has the advantage of being able to handle uncertainties and imprecise data, making it well-suited for use in PV systems, where environmental factors can cause fluctuations in power output.

Recently, four-phase interval boost converters have also gained attention as a promising technology for use in PV systems. This topology has been shown to provide higher efficiency and lower input current ripple compared to traditional boost converters. In this study, we propose a novel approach for maximum power tracking of PV modules using fuzzy logic control and a four-phase interval boost converter. By employing these advanced techniques, we aim to achieve improved performance compared to existing MPPT methods and contribute to the development of efficient and reliable PV systems.

Many energy consumers have been encouraged to seek new supply alternatives, to the detriment of traditional oil-based ones, in order to reduce losses, adapt to environmental measures and, sometimes, improve financial returns. With this, it is possible to see the growth in the use of primary sources based on renewable energy for electricity generation, such as the photovoltaic solar system. The primary energy source of the photovoltaic system is solar, an option with good prospects for a country with high solar incidence, such as Brazil, which has an average annual irradiation that varies between 1200 and 2400 kWh/m^2 [1].

Microgeneration is the production of heat or energy on a smaller scale compared to the production of a fuel-based power plant. Microgeneration systems tend to be located close to load centers, being able to partially or fully serve the load, which can reduce transmission and distribution losses—the issue of loss reduction must always be con-textualized since branches with large The amount of distributed generation can have even greater losses than if they were exclusively load branches and, still, investments must be made in the coordination of protection, since the bidirectional flow can imply in atypical situations. There are several different microgeneration technologies and most of them use renewable energy and not fossil fuels. In this work, photovoltaic micro-generation will be addressed.

Photovoltaic microgeneration plays an important role in promoting energy diversity and alleviating concerns related to energy scarcity and diversification. Photo-voltaic solar cells use energy directly from the sun to generate electricity. The generated electrical energy can be used on-site to meet demand and in case of excess energy, if on grid (the system connects to the distribution grid), it can be exported to the grid.

Photovoltaic systems are renewable, in addition to being easy to install and low maintenance cost. It should be noted that there is a question of net energy balance, that is, there is energy expenditure in the cell manufacturing process that must be compared with the resulting production throughout its useful life—not to mention the type of primary source of energy used in production.

While solar energy can be generated using a variety of technologies, the vast majority of solar cells today start out as quartz, the most common form of silica (silicon dioxide), which can put miners at risk of lung disease silicosis. In addition, the initial refinement of quartz depends on giant kilns, which require a lot of energy—which often has non-renewable resources as its primary source. The next step would be the trans-formation of metallurgical silicon into a purer form, which ends up generating very toxic substances. These factors can be seen in greater depth in [2]. Toxicity is not the only concern. The original energy investment pays off only after years, since producing solar cells requires a lot of energy.

Solar radiation is variable, requiring the use of a treatment and control system that provides the necessary regularity for the best operation of the solar modules. In addition to the control system, an energy storage system is also needed.

In the photovoltaic solar system, sunlight is used to generate energy, which makes it impossible to produce at night and this storage is necessary, a process currently with high cost, and over time it has been chosen to work with idleness in the offer than to invest in storage. In this case, solar energy is used to save the consumption of other primary, simpler storage sources, such as thermal energy.

Still, some smaller systems employ on-site storage via batteries, which can be lithium, lead-acid, or nickel-cadmium. Batteries improve the quality of energy supply and allow for an efficient expansion of distribution networks—the use of inventory al-lows minimizing the use of the infrastructure associated with product distribution, in addition to being an effective part of the solution against interruptions or instabilities in supply of electricity [3].

However, battery use involves positive (storage) and negative technical aspects (short useful life compared to other electronic equipment, although recent studies indicate that this must be overcome, and the extent to which prices have been reduced. In the solar PV system, there are no obvious choices. It's all a matter of balancing positive and negative aspects, often in conflict with each other.

2. Materials and Methods

The strategy employed in this work is to present each element of the proposed architecture during its presentation, that is, in micro-themes: Photovoltaic Modules, DC-DC Converters, Tracking of the point of maximum energy generation.

The system architecture is presented in **Figure 1**.

From the diagram, the modules that are part of the study can be defined, some will not be analyzed in depth in, and others may be suppressed due to advances in studies of the new technologies used today, but it is presented for a complete view of the project:

1) Photovoltaic module: converts solar energy into electricity. The output is current and feeds the input of the boost or boost DC-DC converter.

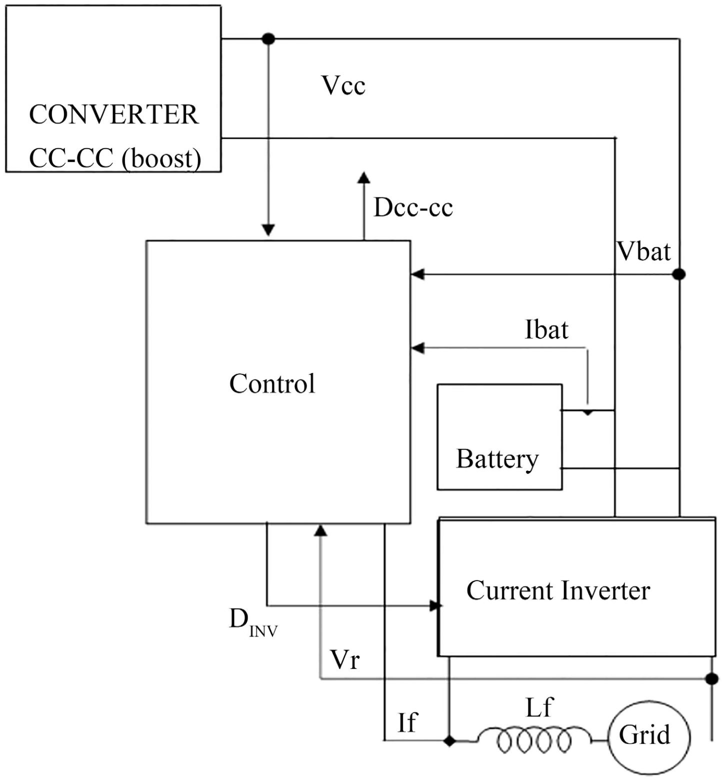


Figure 1. Architecture of the studied system. Elaborated by the author.

2) Elevator or boost converter: emulates a variable resistance, to ensure maximum energy transfer at each operating point of the photovoltaic cell, which depends on ambient temperatures and insolation.

3) MPPT: monitors the cell variables and changes the input resistance characteristic, observed by the photovoltaic module, of the DC-DC converter by changing the duty cycle.

4) Battery: stores energy that is not sent to the electrical grid.

5) Current inverter: controls the flow of active and reactive power, as well as compensation of distortion harmonics or voltage drops, if necessary.

6) Control: microcontroller that implements the control laws of the output stages.

The objective of the article is to employ non-linear control techniques to control the energy flow of photovoltaic modules at the module's maximum power point. In turn, the energy flow control strategy for the grid will be based on classical controllers. Thus, there are two control loops, one to track the module's maximum power generation point and the other to control the energy flow to the grid.

2.1. Photovoltaic Cells

The photovoltaic cell is a semiconductor device that converts sunlight into electricity through the photovoltaic effect. It was developed in the early 1950s for satellites, initially a very expensive technology. However, with the advancement of production techniques, it has become economically viable even for supplying homes and businesses. The most used material in the production of solar cells is Silicon, which can be applied in different ways [4].

Photovoltaic cells are semiconductor devices that convert sunlight into electricity, while photovoltaic modules consist of photovoltaic cell circuits sealed in an environmental protection laminate and are the fundamental building block of photovoltaic systems. The modules are several cells connected in parallel for the purpose of increasing current, and in series for a high voltage. Photovoltaic panels include one or more photovoltaic modules mounted as a field-installable unit.

For study, it is necessary to have a mathematical model that relates the electrical variables, current and voltage, with some environment variables such as insolation and temperature. Thus, the equations are developed from a set of physical relationships al-ready established and the models obtained present simulation results of a photovoltaic module compatible with the commercial module and its catalog data, that is, the simulated I-V characteristics are practically identical to the catalog [5].

One of the phases of this work is to simulate the behavior of a photovoltaic cell and, for this, an equivalent electrical circuit was used as in [6]. It consists of a current source, a diode in parallel and a resistor in series and another in parallel. The current source is the representation of the electric current produced by the radiation absorbed by the cell, the diode is the PN junction, and the resistances are used to limit the cell capacity, the modeling accuracy is better when these idealities are represented by the resistances are considered.

For the equivalent circuit simulation, the characteristics provided in the data sheet of the CS6K-260|265|270|275 P module manufactured by Canadian Solar were used, so that the approach and formulas presented in (CASARO, M.M.; MARTINS D.C., 2008), which equate the circuit, as follows:

$$I = Iph - Ir\left[e^{\frac{q(V+I\cdot Rs)}{y\cdot k\cdot T\cdot Ns}} - 1\right] - \frac{V + I\cdot Rs}{Rp} \quad (1)$$

$$Ish = \frac{V + I\cdot Rs}{Rp} \quad (2)$$

where:

V, I—Voltage and current at the output terminals of a solar cell;

Iph—Photocurrent (A);

Ir—Reverse cell saturation current (A);

Rs, Rp—Cell series and parallel resistance (Ω);

q—Charge on the electron, 1.6×10^{-19} C;

η—Quality factor of the p-n junction;

k—Boltzmann constant, 1.38×10^{-23} J/K;

T—Ambient temperature, K.

The solution of Equation (1) results in the I-V characteristic of a cell. The Iph and Ir values are calculated according to Equation (3) and Equation (4).

$$Iph = Isc + \alpha\left(T - 298\right)\cdot\frac{Psun}{1000} \tag{3}$$

$$Ir = Irr\left(\frac{T}{Tr}\right)^3 \cdot e^{\left[\frac{q\cdot EG}{\eta\cdot k}\cdot\left(\frac{1}{Tr}-\frac{1}{T}\right)\right]} \tag{4}$$

where:

Isc—Short-circuit current per cell, (A).

α—Temperature coefficient of Isc.

Tr—Reference temperature, 298 K.

$Psun$—Solar radiation intensity, W/m^2.

Irr—Reference reverse saturation current (A).

EG—Gap band energy, 1.1 eV.

It is also known that when the current I is equal to zero, V = Voc (open circuit voltage per cell). Adopting this point of characteristic, I-V and making T = Tr, Equation (5) is obtained from Equation (1).

$$Irr = \frac{Isc}{e^{\frac{q\cdot Voc}{\eta\cdot Ns\cdot k\cdot T}} - 1} \tag{5}$$

Using the above equations, the standard test conditions (STC) and the CS6K-260|265|270|275 P module data sheet, manufactured by Canadian Solar, the simulation can be performed.

Based on the 270P model, the most important information is:

Open circuit voltage (Voc) = 37.9 V;

Short-circuit current (Isc) = 9.32 A;

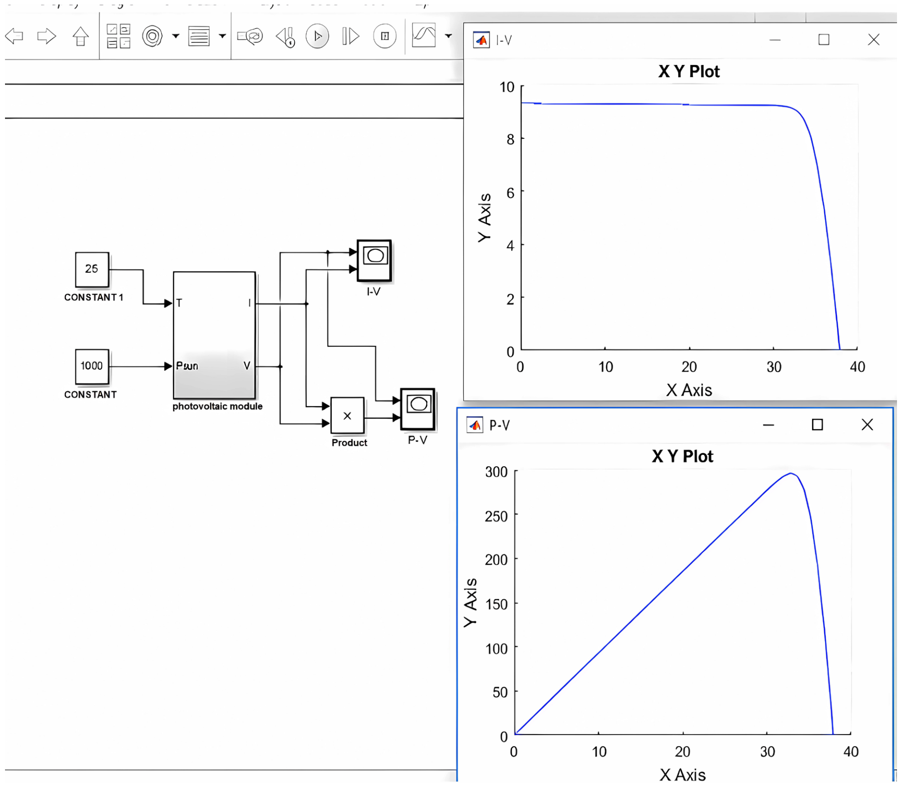
Operating voltage opt. (Vmp) = 30.8 V;

Operating current opt. (Imp) = 8.75 A.

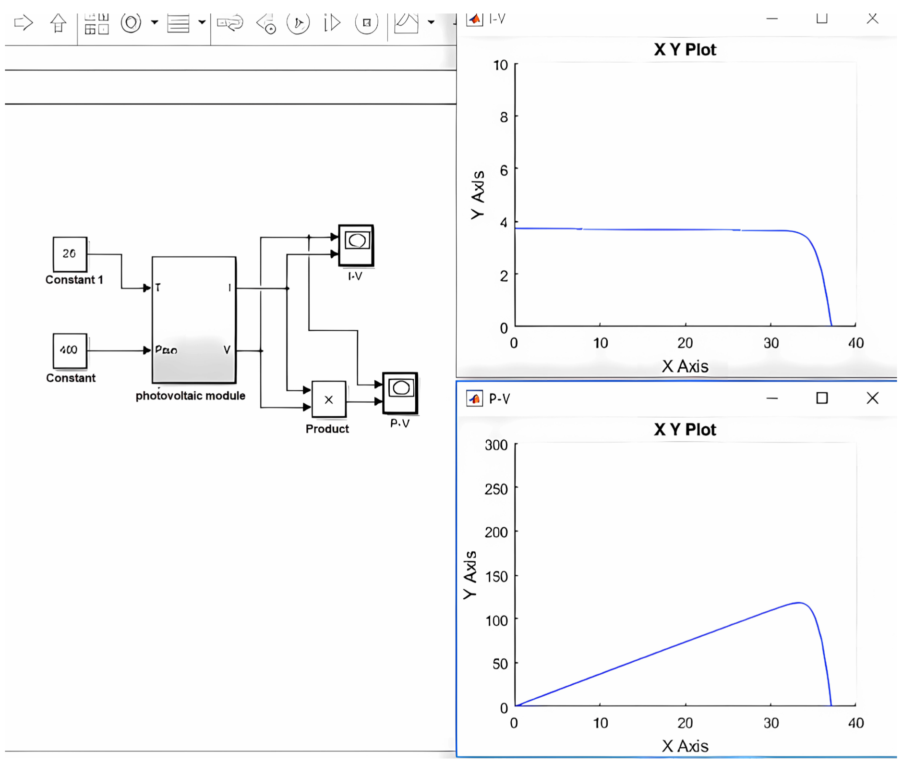
Equations (1) to (5) can be simulated using MATLAB/Simulink® math blocks. In addition to being possible the final comparison between the results obtained from the model and the one available in data sheets, for a cell. In **Figure 2(a)** we have the model made in simulation for irradiation of 1000 W/m^2 and in **Figure 2(b)**, for irradiation of 400 W/m^2, which can be compared with the catalog results shown in **Figure 3**.

Based on **Figure 2(a)**, **Figure 2(b)** and **Figure 3**, it is possible to conclude that the model adequately represents the real module. Looking at the upper graph of **Figure 2(a)** (I-V curve graph) in the graph for irradiation of 1000 W/m^2 the output current is close to 9 A, for the voltage range from 0 to a value just above 30 V, and then drops abruptly, close to 40 V, as also occurs in the curve of the data sheet (**Figure 3**). And in the upper graph of **Figure 2(b)** (I-V curve) the graph for irradiation of 400 W/m^2, similar behavior occurs, the current is situated at 4 A, from 0 to close to 35 V, when it drops abruptly to zero at 40 V, as it occurs for the same irradiation in **Figure 3** (data sheet).

In this sense, the model used in this study is consistent with the catalog data, which is important for the correct design of the following steps.



(a)



(b)

Figure 2. This is a figure where: (a) I-V curve (upper graph) and P-V (lower graph) for 1000 W/m^2 irradiation; (b) I-V (upper graph) and P-V (lower graph) curve for 400 W/m^2 irradiation.

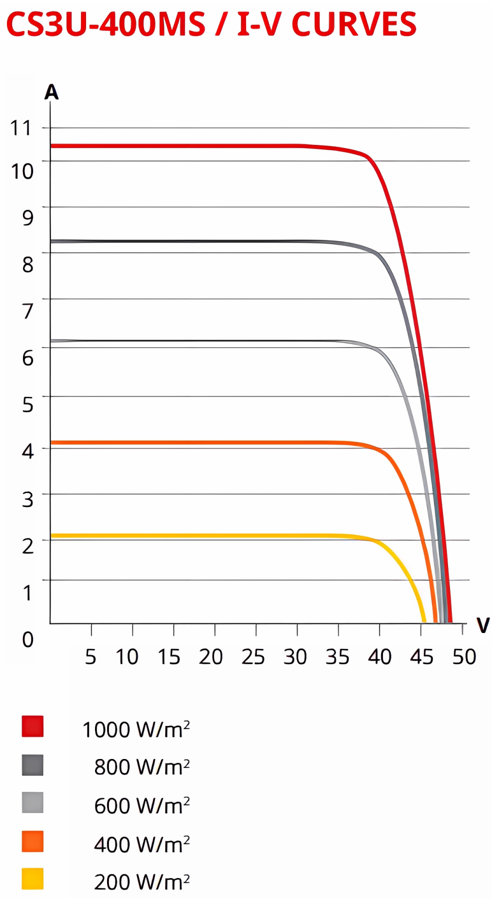


Figure 3. CS6K-260|265|270|275 P module data sheet—Canadian Solar.

2.2. Principle of Maximum Power Transfer

The maximum power transfer theorem provides the condition in which the load resistance or impedance must satisfy for maximum energy absorption from the source network. The theorem says that the power transferred to the load is maximum when the internal resistance of the source is the same as the resistance of the load.

The model presented for the photovoltaic cell can be reduced to a voltage source in series with a resistance. To understand the maximum transfer theorem, this source is connected to a load with variable resistance (in the system under study, this variable load will be performed by means of a DC-DC converter). Maximum transfer occurs when the value of the resistance R and the internal resistance of the source Ri are equal. In other words, the maximum power dissipated occurs at the load.

Thus, as for each operating point there is a distinct photoelectric current, there is a variation in the internal resistance of the source. Therefore, for each operating point there will be an optimal load resistance, that is, a load value that allows the maximum possible energy production. The search for this optimal point led to the study and elaboration of maximum power tracking techniques, MPPT.

In general, these techniques use the current and voltage values of the module, corresponding to this point of maximum power, to change the input impedance of the converter so that it intercepts the point of maximum power instantaneously. As the photovoltaic cell presents variable impedance as a function of the insolation and temperature parameters, which reflect on the current and voltage, it is necessary to vary the load resistance continuously. Therefore, a DC-DC converter will be used.

2.3. Maximum Power Point Tracking (MPPT)

The maximum power point tracking (MPPT) is an algorithm that includes load controllers used to obtain the maximum power available in the PV module under certain conditions. Maximum power varies with ambient temperature, solar cell temperature and solar radiation. Being most effective in cold weather, cloudy or foggy days or when the battery is heavily discharged.

The main principle of tracking the maximum power point is to obtain the maxi-mum power available from the PV module, making it operate at the most efficient voltage. From the use of DC-DC converters between the photovoltaic module and the load, it is possible to establish the operation at the point of maximum efficiency.

Methods for Executing the MPPT

In most techniques, referring to maximum power tracking, voltage and current output signals from the photovoltaic module are used. Among the most used methods in the literature, there are: Constant Voltage, Disturb and Observe and Incremental Conductance. Briefly:

- Constant voltage: it is a constant maximum power point algorithm that automatically adjusts the reference voltage, it is considered one of the most used techniques in photovoltaic systems.
- Disturb and Observe (P&O): A slight disturbance is introduced into the system. If the power increases due to this perturbation, then the perturbation remains in that direction. After the maximum power is reached, the power at the next instant decreases and therefore the perturbation reverses. When steady state is reached, the algorithm oscillates around the peak point. To keep the power variation small, the perturbation size is kept very small. A controller acts by moving the module's operating point to that specific voltage level. It is observed that there is some loss of power due to this disturbance and it also fails to track the power under rapidly changing atmospheric conditions.
- Incremental Conductance: it can be determined that the MPPT has reached the MPP and stops the disturbance of the operating point. This algorithm has advantages over P&O as it can determine when the MPPT has reached the MPP. In addition, incremental conductance can quickly track rising and falling irradiance conditions with greater precision than it disturbs and observes. The downside is increased complexity.

2.4. DC-DC Converters Emulating Variable Load

DC-DC converters are systems formed by power semiconductors operating as switches, and by passive elements, usually inductors and capacitors, whose function is to control the power flow from an input source to an output source [7].

The DC-DC converters have high voltage gain, high efficiency, and work like an electronic transformer, that is, in this analogy it can be said that the impedance of the secondary (output) is reflected in the primary with the square of the transformation ratio—which in the case of a DC-DC converter it is the static gain. The proper operation of a converter means that they supply and share the energy demanded by the load in a homogeneous and balanced way.

The static gain of the converter is the ratio between the average value of the output voltage and the average value of the input voltage. When this ratio has a value greater than 1 (one), the converter is called a step-up, and when this ratio has a lower value, it is called a step-down converter. In this work an elevator type converter is used to emulate a load with variable resistance.

Boost Typology with Four Keys (Elevator)

The Boost converter is a step-up DC-DC converter, which produces an average value of the output voltage greater than the average value of the input voltage. Its main characteristics are that it can only increase the output voltage, the output current is discontinuous, and the input current is of good quality. It features input current source and output voltage source.

To model the circuit, it is observed which are the variables associated with the energy storage elements of the system, in this case, the voltage in the capacitor and the current in the inductor. Converter modeling is performed in this work.

2.5. Pulse Width Modulation—PWM

To perform the entire system for simulating the control of the photovoltaic cell, in addition to the cell and the Boost converter, a block diagram was also used to implement pulse width modulation or pulse width modulation, PWM.

A boost converter, as seen, operates in two stages of operation, based on the conduction or blocking of the switch. To determine these times, a modulation technique is used, which consists of comparing a sawtooth wave signal, with amplitude, Vp, and frequency, fs, constants, with a modulating signal that represents the time to be maintained the leading switch.

As soon as the sawtooth amplitude exceeds that of the modulator value, the comparator output voltage is zero. This repeats at every interval, since when the saw-tooth reaches its maximum value, it instantly returns to zero.

2.6. Boost Converter Input DC Bus

As the photovoltaic module has an output characteristic to emulate a current source and the boost converter also has an input characteristic to emulate a current source, a component must be used to make coupling of both, since it is not possible to associate power sources series current. For this, a coupling capacitor is used, which has voltage source characteristics.

3. Results

The diagram of the system implemented in SIMULINK, containing the photovoltaic module, the PWM module and the traditional boost converter—the idea was to study a simpler structure, to understand the dynamics of definition of fuzzy functions and fuzzy rules, is shown in **Figure 4** elaborated by the author. From it, it is possible to perform several simulations.

To perform the simulations, it is necessary to define the parameters of the converter, among them: bus capacitor, boost input inductor, boost output capacitor, load value, duty cycle for the maximum and minimum operation points, switching frequency, etc.

In the simulation at the operating point, insolation of 1000 W/m^2, temperature of 25˚C, duty cycle of 0.48, it is possible to observe the output power graph, as shown in **Figure 5**. It is observed that the module output voltage stabilizes at 32 V and the current at 9.2 A, approximately, confirming the module data obtained from the catalog. Additionally, the output voltage is at 60 V as designed and the load current at 4.7 A. As the system is in open loop, there is an overshoot in the inductor current, but the objective at this moment is to evaluate the operation in static regime.

The simulation was repeated, changing only the insolation to 400 W/m^2, **Figure 6**. Note that by not changing the duty cycle, the module failed to produce the maximum possible power for this irradiation, due to was going to expect approximately 118 W, but got approximately 50 W. To correct this situation, the

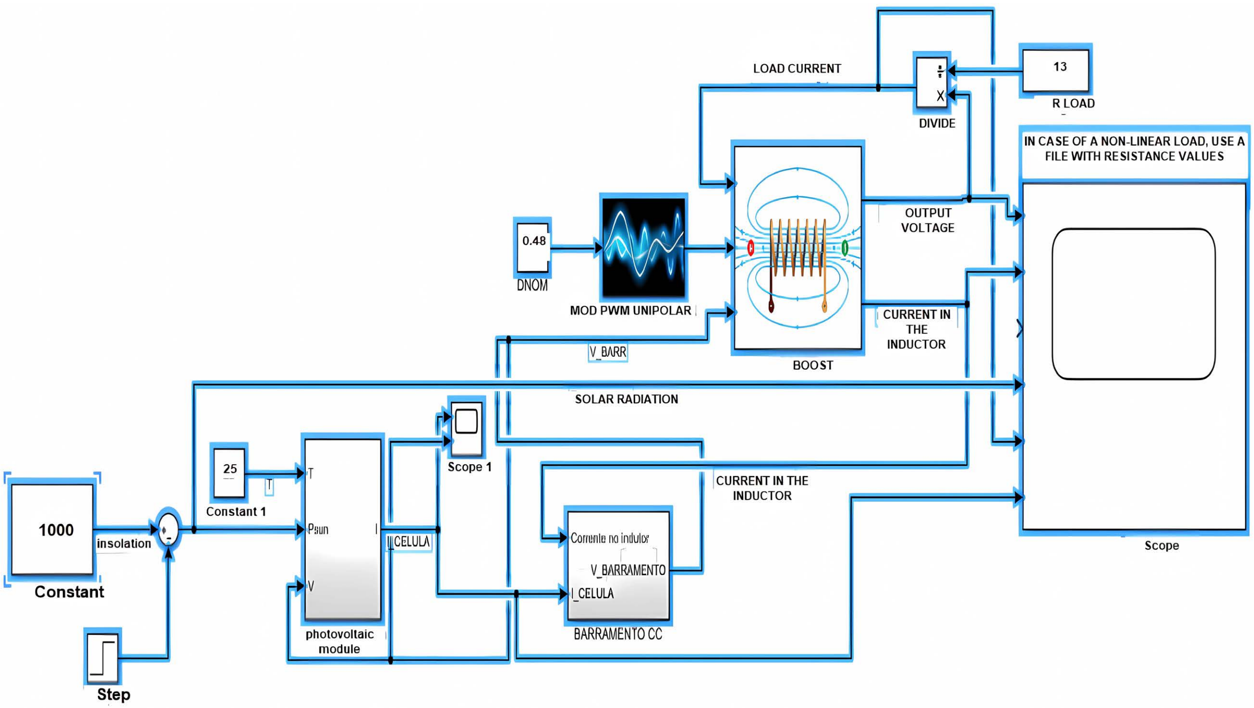


Figure 4. Schematic: photovoltaic module, boost converter.

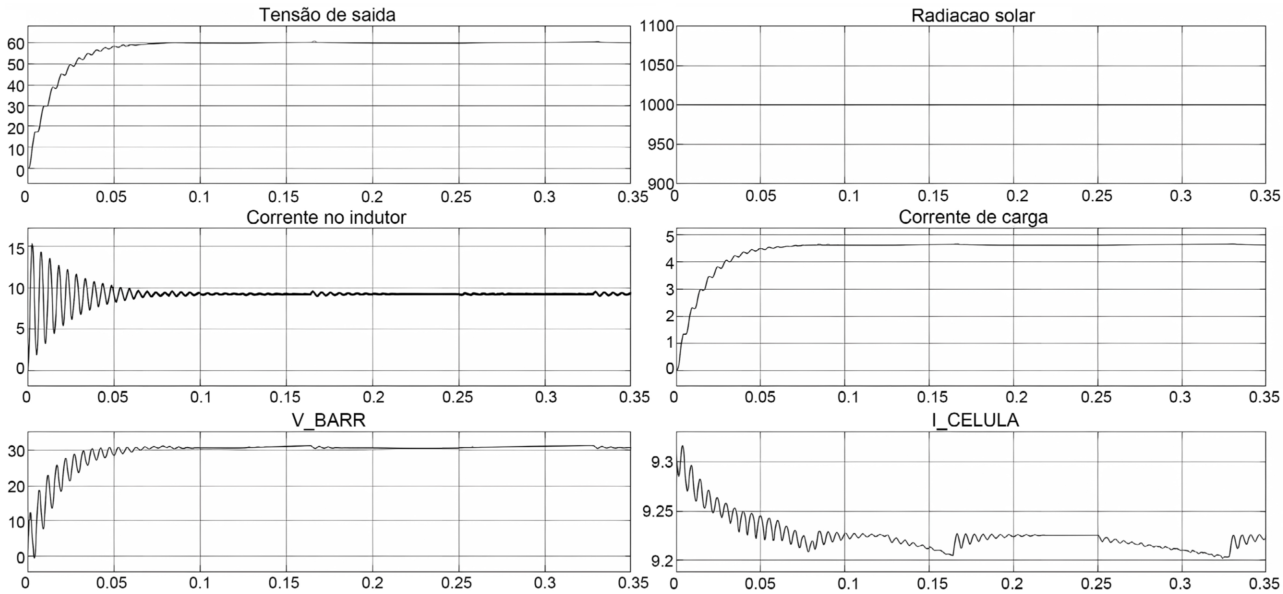


Figure 5. Main results for the boost converter with an incidence of 1000 W/m^2.

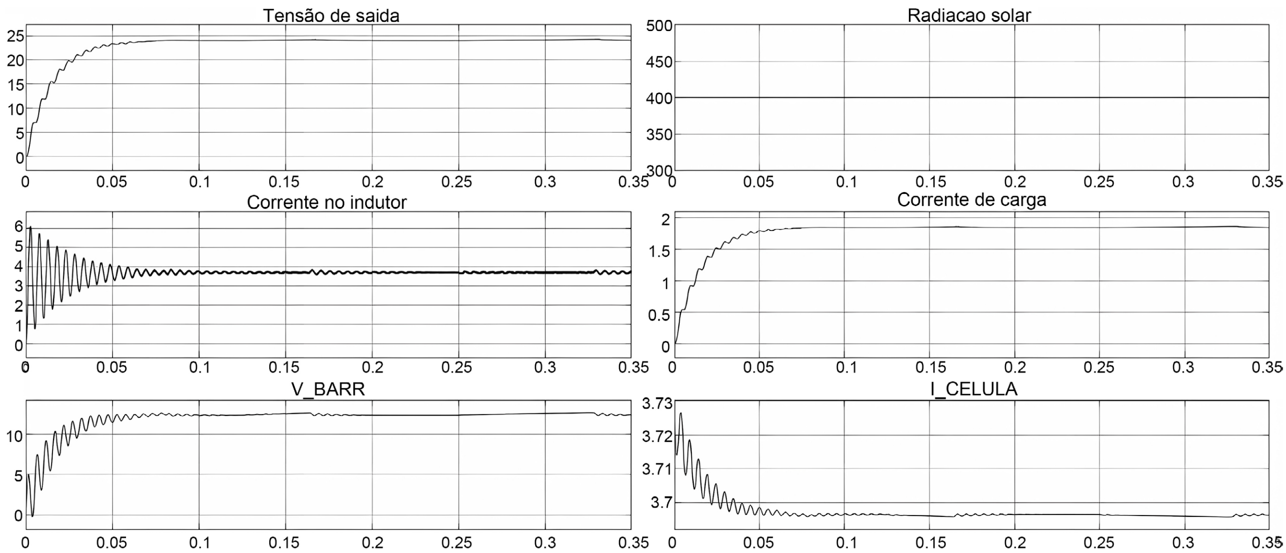


Figure 6. Main results for the boost converter with an incidence of 400 W/m^2.

duty cycle was changed to restore the maximum power point. Adjusting the value to 0.18, the power of the module approaches the expected value of 110 W.

4. Discussion

At the end of this initial simulation and using it for comparison, the fuzzy controller and the traditional boost converter were implemented, initially, and then the interval boost converter in order to find the duty cycle directly. The use of the fuzzy logic controller, which has a wide range of applications in the area of renewable energies, can optimize the process.

The use of fuzzy controllers is said to be simple, with imprecise inputs and without the need for a well-defined mathematical model, in addition to dealing with non-linearity [8]. This controller is used to obtain the maximum power that the photovoltaic modules can produce, under variable weather conditions.

Based on the first simulation made, it was noticed that it was necessary to change the duty cycle so that the maximum power point was reached for the insolation of 1000 W/m^2 and 400 W/m^2. To carry out the control, the variation of power and voltage of the module is used as input fuzzy variables, and the variation of the duty cycle is used as output variables.

4.1. Implementation of Fuzzy Controller—Traditional Boost

A fuzzy controller is based on determining the controller by observing the user's experience, so the behavior of the control variable must be modeled through well-defined rules. For this, the power curves of the module and the power curve of the converter are used, based on the control variable, the duty cycle. The modeling followed the steps defined in a similar work (it employed a buck-boost in the case) [9], facilitating the process.

The graph in Figure 7 shows the behavior of the power and voltage of a photovoltaic module. Still, there is, considering a load of 13.2 Ω, the input power, disregarding losses, for different cyclical ratios for the boost converter.

It should be noted that it is the irradiation curve of 1000 W/m^2; on it there is a point P1, which represents the power absorbed by the converter at a given instant of time, which is the power and voltage condition of the cell and, it can be seen, that it is to the left of the maximum power point. At this point on the curve, considering that the irradiation is constant, the point can move either to the left or to the right, changing the duty cycle of the converter.

The output current can be considered constant in the analyzed period of time, it is observed that the variation of the voltage in the bus capacitor, therefore in the cell, depends on the duty cycle. If the duty cycle is reduced, the current I0 is reduced, causing a positive change in voltage, shifting the point to the right. In that case, you have to:

Hypothesis 1: the differences are both negative. This means that the point

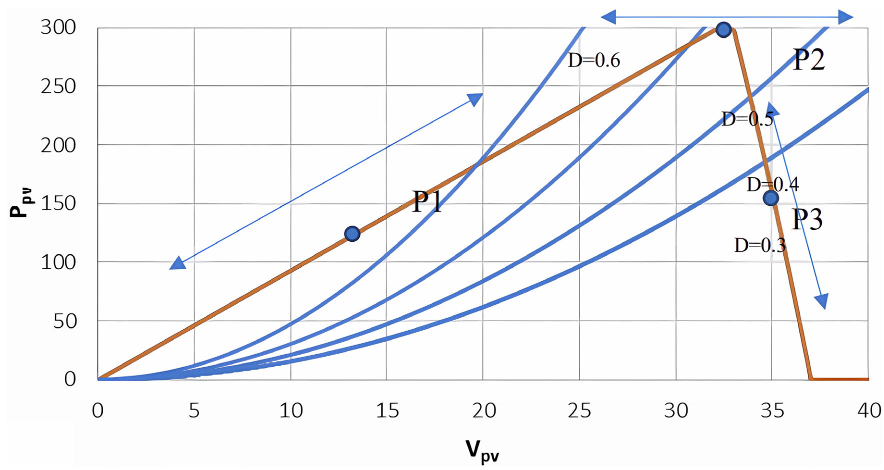


Figure 7. Feature of photovoltaic module.

moves away from the point of maximum power. In this case, the duty cycle must be reduced to compensate for this reduction.

Hypothesis 2: the differences are both positive. This means that the point moves towards the point of maximum power. In this case, it is also recommended to reduce the duty cycle. However, it may happen that P1 is very close to the maximum point and, if the step is too high, it is located to the right of it, causing an inversion of the power signal. This can lead to fluctuations and therefore must be considered in the analyses.

Now, analyze point P2. At this point, it is assumed that the voltage and power variations are close to zero. This means that this point is close to the point of maximum power. In this situation, the most appropriate thing is to keep the cycle ratio constant.

Now, analyze point P3. At this point, it is assumed that the voltage and power variations are in opposite directions, that is, if the voltage variation is positive, the power variation will be negative. This is because it is to the right of the maximum power point. So:

Hypothesis 1: the power variation is positive and the voltage variation is negative. This means that the point moves to the point of maximum power. In this case, the duty cycle must be increased to compensate for this reduction. Entering this region, the variation is sudden and it may occur, depending on the step of the duty cycle, that the point moves to the left of the maximum point, causing an oscillation or fluctuation. Consider very small steps.

Hypothesis 2: the power variation is negative and the voltage variation is positive. This means that the point moves in the opposite direction to the maximum power point. In this case, it is also recommended to reduce the duty cycle with a significant step.

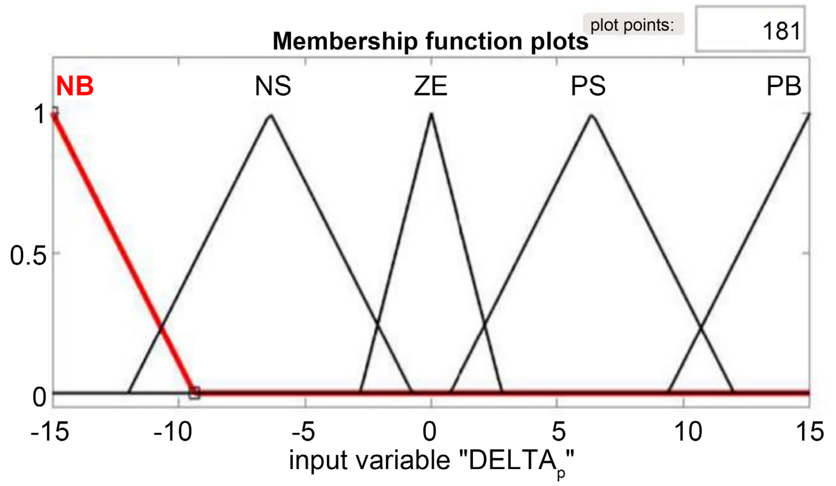
When one of the differences, voltage or power, is zero, it is suggested to leave the duty cycle unchanged, as it is not possible to determine whether the system is to the right or left of the maximum power point.

The basic idea is to use the module power curve as the input data set for the fuzzy controller and the duty cycle as the output variable. Five terms were defined for the variables for their description (big negative, NB; small negative, NS; zero, Z; small positive, PS; large positive, PB) depending on the variation of each variable in relation to the value obtained in the event immediately previous. In turn, fuzzy logic, universe of discourse, is used to relate the set of fuzzy inputs with the output.

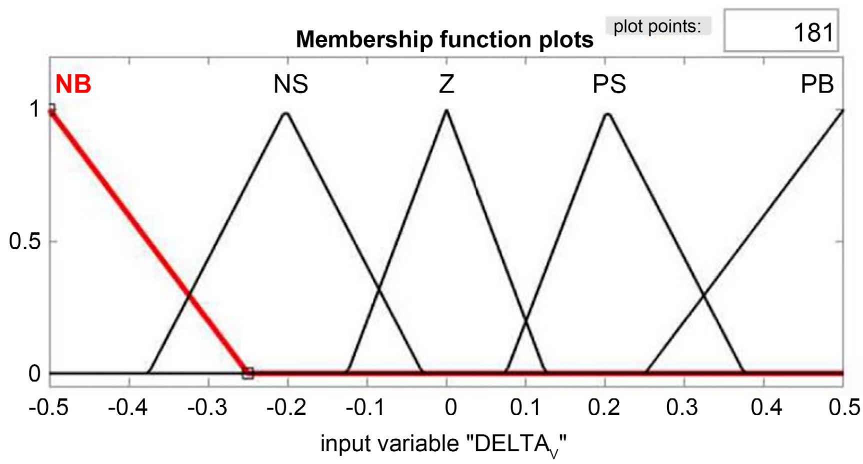
In this work, the definition of limits for each of the descriptions of the variables was done through simulations. In **Figures 8(a)-(d)** are the result of the fuzzy functions of input, power and voltage, and output, duty cycle.

In order to test the fuzzy controller, the irradiance variation was simulated with steps of 200 W/m^2, starting with 400 W/m^2, using the boost converter. The update frequency of the fuzzy controller, in the simulations, was 1 kHz.

The way the fuzzy rules were inserted in the Simulink Fuzzy Controller and their corresponding graphs are shown in **Figure 9**. In addition, the 3D visualization of the output can be seen in **Figure 10**. It is possible to see that with the maximum voltage variation and minimum power; you have the maximum duty cycle. And equally, with maximum power and minimum voltage, there is also the maximum duty cycle.



(a)



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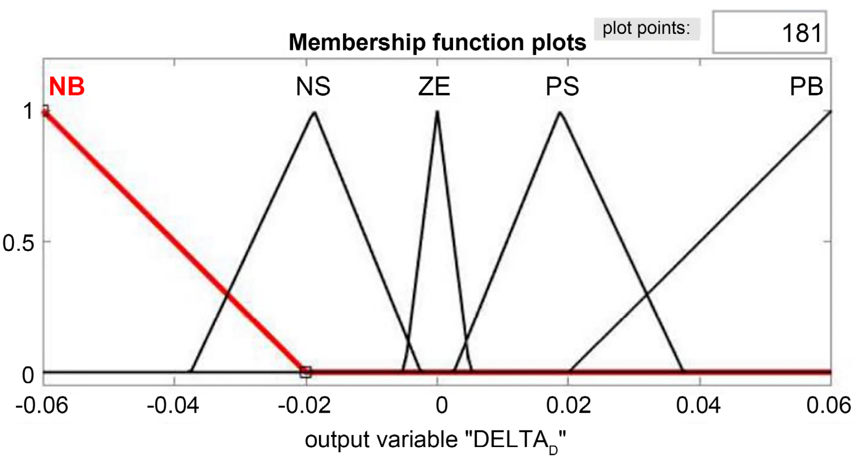

(c)

DP / DV	NB	NS	Z	PS	PB
NB	*NB*	*NS*	*Z*	*PS*	*PB*
NS	*NS*	*NS*	*Z*	*PS*	*PS*
Z	*Z*	*Z*	*Z*	*Z*	*Z*
PS	*PS*	*PS*	*Z*	*NS*	*NS*
PB	*PB*	*PS*	*Z*	*NS*	*NB*

(d)

Figure 8. This is a figure. Where: (a) Input Fuzzy Function—Power; (b) Input Fuzzy Function—Voltage; (c) Output Fuzzy Function—Cycle Ratio; (d) Set of Fuzzy rules used.

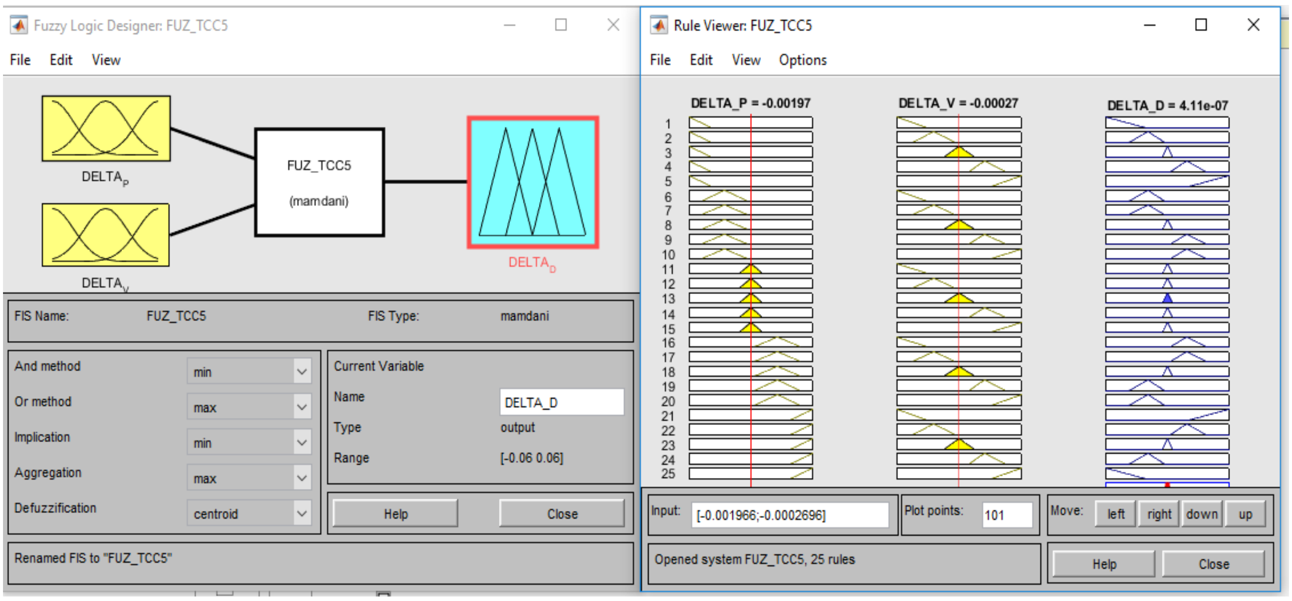

Figure 9. Logic block fuzzy controller and corresponding output graphics.

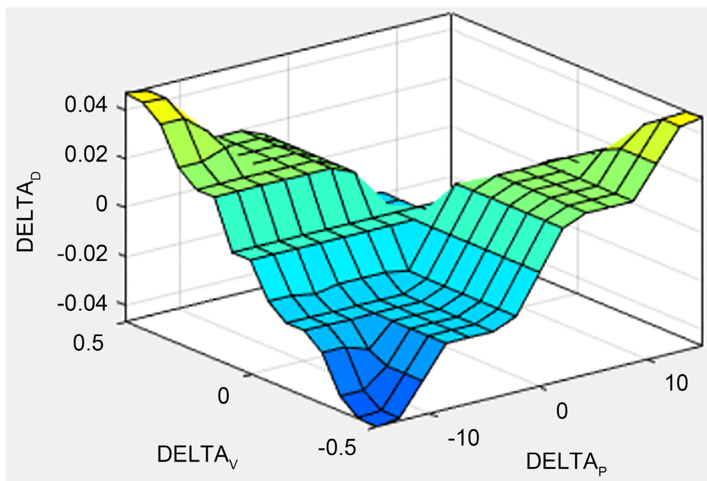

Figure 10. 3D visualization of the fuzzy controller in Simulink.

In the graphs of **Figure 11**, below, there is the system response with different degrees of insolation, every 200 ms, of 200 W/m^2. It is observed, by the simulations, that for each level of irradiation, the controller acts trying to maximize the power generated by the photovoltaic module. It should be noted that it is also possible to improve the dynamic and static response by changing the scale definitions for the fuzzy variables.

4.2. Implementation of Fuzzy Controller—Interval Boost

The modeled circuit of the interval Boost converter is shown in Figure 12 and using it in the simulation, it is possible to observe different results of the fuzzy

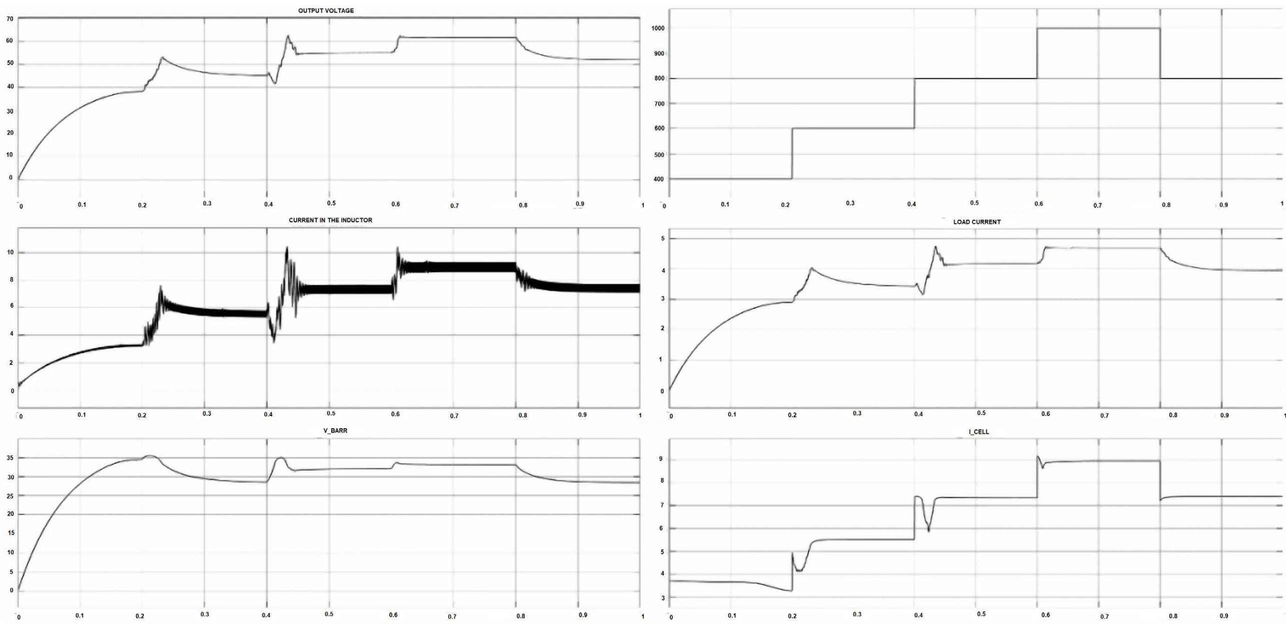

Figure 11. Simulation results of the boost converter with different irradiations.

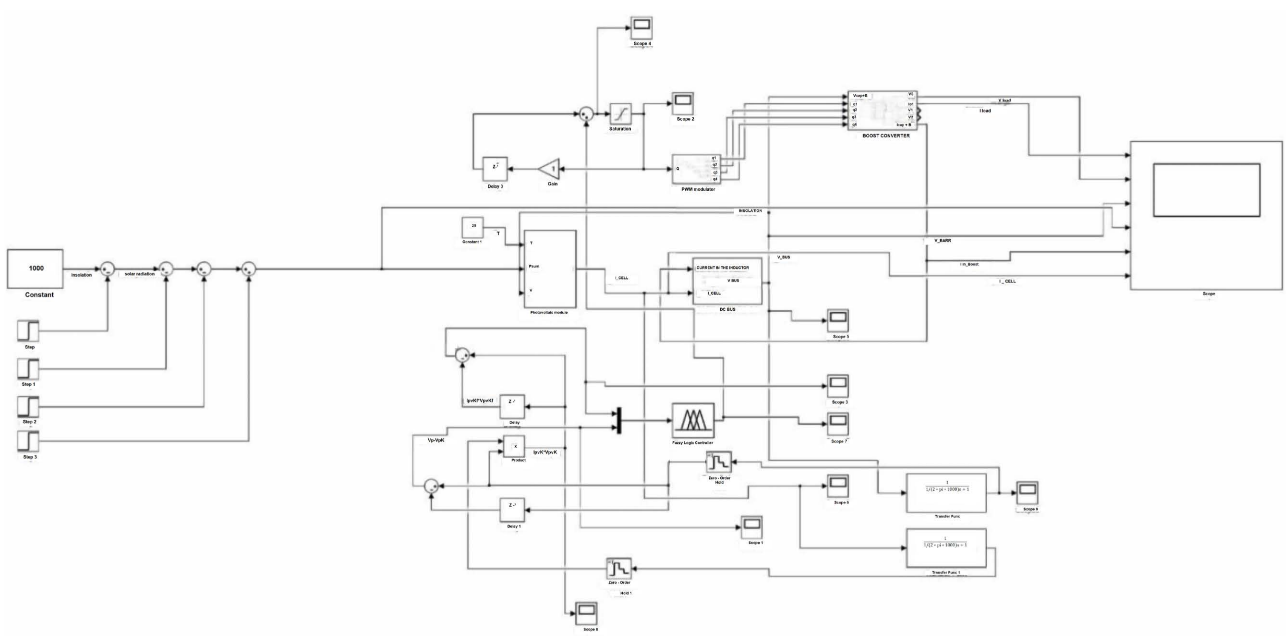

Figure 12. Modeled circuit of the interval boost converter.

controller when compared to the traditional Boost converter. First, it is necessary to find the new characteristics of the photovoltaic module, where the resistance and duty cycle value are changed.

In the graph of **Figure 13** it is possible to observe the behavior of power and voltage in a photovoltaic module. Considering a load of 254 Ω, a graph similar to that found in conventional Boost is obtained, but now with different duty cycle values.

The point P1, which represents the power absorbed by the converter at a given instant of time, which is the power and voltage condition of the cell, is to the left of the maximum power point. At this point on the curve, considering that the irradiation is constant, the point can move either to the left or to the right, changing the duty cycle of the converter.

Point P2 is at the maximum power point of the curve and point P3 is to the right of the maximum power point. In point 3, also considering that the irradiation is constant, it is necessary that the point moves to the right or to the left, changing the duty cycle, in order to seek the maximum power point of the photovoltaic module.

The hypotheses made for the conventional boost converter can also be used in this example, changing only the intervals, since the fuzzy rules remain the same. Regarding the ranges, that of the input fuzzy function—power remains the same, the range of the input fuzzy function—voltage is changed previously from −0.5 to 0.5 to −0.1 to 0.1 and the range of the duty cycle of −0.06 to 0.06 to −0.03 to 0.03.

The graphs in **Figure 14** show the variation in power, variation in voltage and duty cycle, and it is possible to see that both coincide at a point where the voltage to power ratio is maximum, generating a duty cycle that results in the point of maximum power of the photovoltaic module.

In order to test the fuzzy controller together with the interval boost converter, the irradiance variation was simulated with steps of 200 W/m^2, starting with 1000 W/m^2. In **Figure 15**, there is the response of the system with different degrees of insolation.

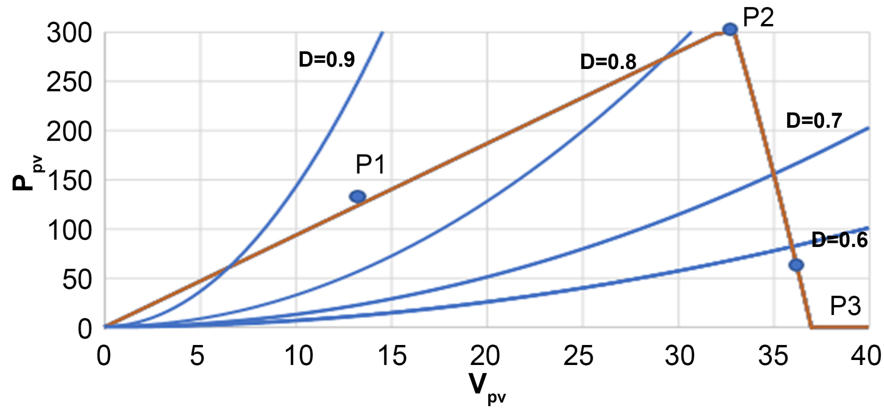

Figure 13. Features of the photovoltaic module—Interval Boost Converter.

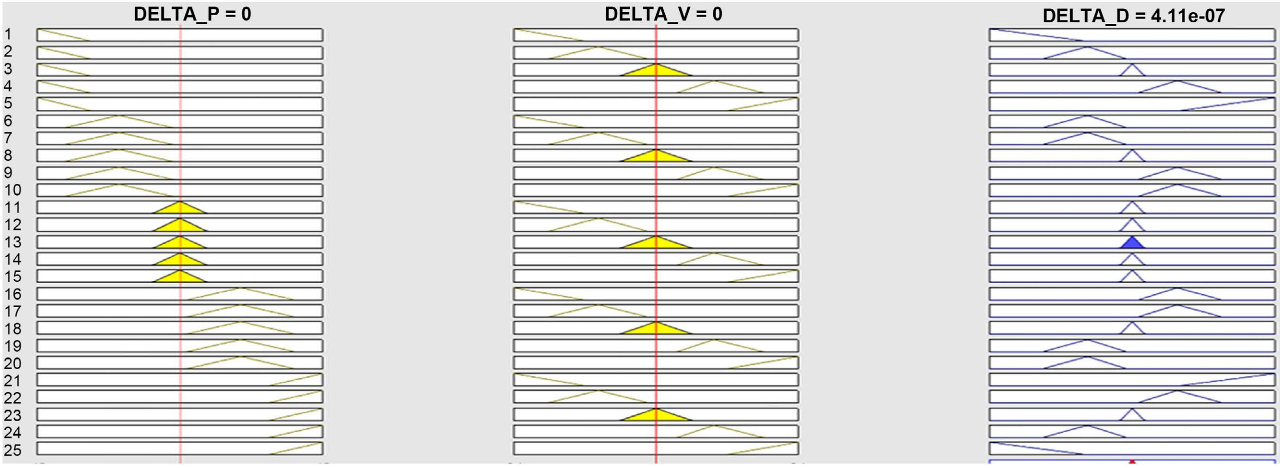

Figure 14. Output graphics.

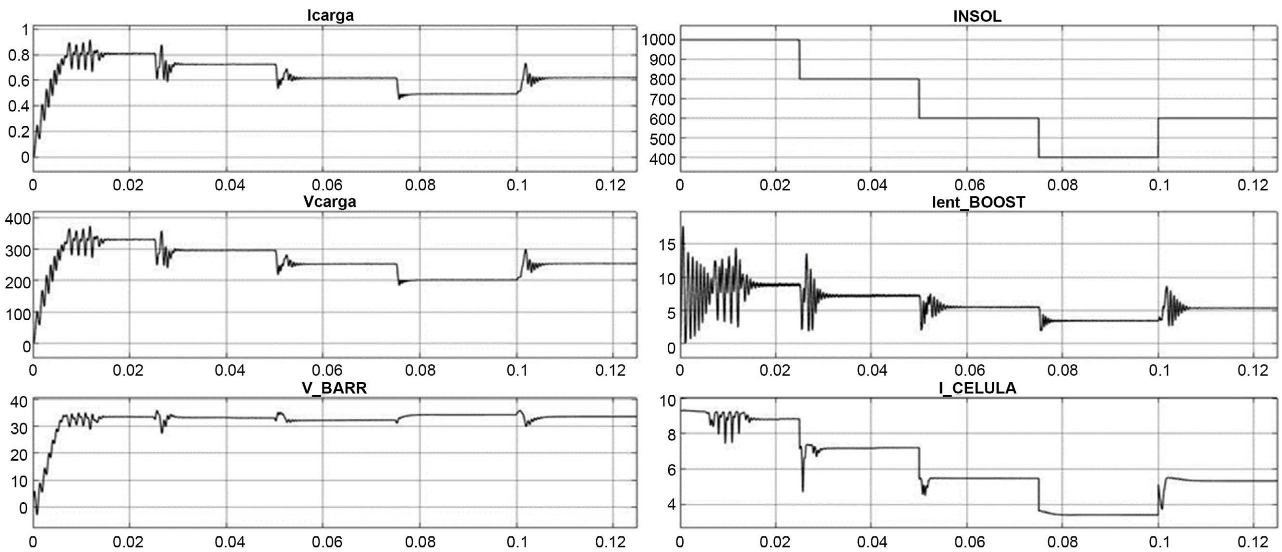

Figure 15. Simulation of the interval boost converter with different irradiations.

It is observed, by the simulations, that for each level of irradiation, the controller acts trying to maximize the power generated by the photovoltaic module. At the be-ginning of the graphs, it is possible to notice a large oscillation, this is due to the start transient, where there is a more sudden variation (from 0 to 1000 W/m^2). It is possible to improve the response, dynamics and statics, by changing the scale definitions for the fuzzy variables.

4.3. Current Inverter

The initial idea, to process the energy from the module to the network, was to use the following circuit (Ayres, 1996). There is a step-down converter (S1) that generates a 120 Hz rectified sinusoidal current. This current passes through a current inverting stage (S2-S5). The step-down converter has a voltage loop to control the DC link voltage and a current loop to ensure a waveform similar to the grid. At the output of the current inverter stage there is an LC filter to minimize

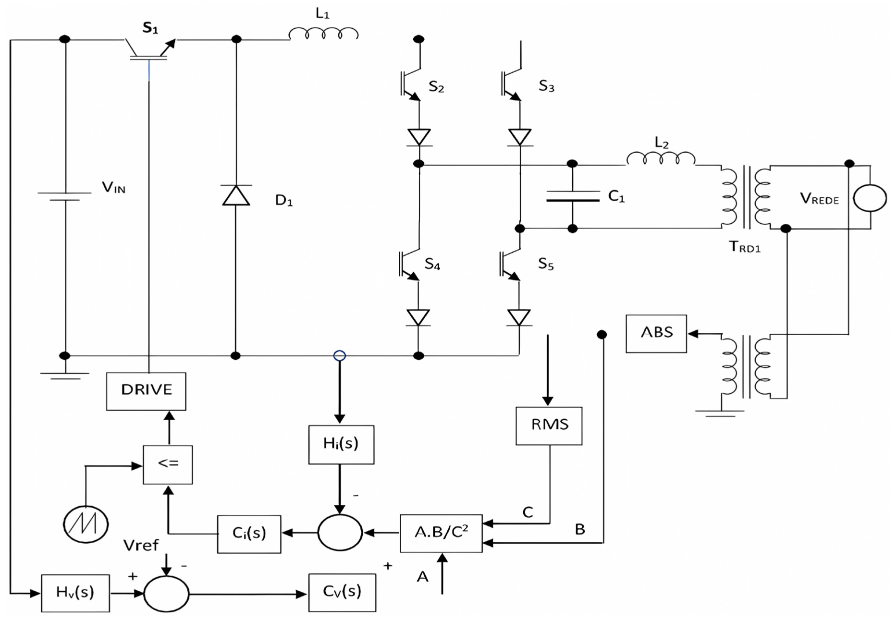

Figure 16. Current inverter circuit. Source: Ayres, 1996 [10].

harmonics due to high-frequency switching and an isolating transformer and mains voltage adapter, as show in **Figure 16**.

Note that this converter has a constant voltage and a rectified sinusoidal current at the input. This results in a variable power flow, resulting from the product of current and voltage. Note that the input to the capacitor is the interval boost converter power flux, which is constant; thus, the capacitor absorbs variations between the step-down and input current, resulting in voltage ripple.

The control strategy employs the signal module of the voltage source in which the energy will be regenerated (signal B). This has its amplitude modulated by the signal A, coming from the voltage compensator of the converter. However, the reference voltage source varies in amplitude, to avoid the effect of this variation, it is normalized by d-viding by the effective value. Additionally, a feed forward action is introduced, dividing again, that is, if the AC bus voltage changes, there is a command action to compensate for this disturbance. Regarding this stage, it was not possible to integrate with the previous stage. However, it is suggested that the study continue.

5. Conclusions

The fuzzy controller is suitable for dealing with power variation due to environmental changes. Although algorithms with alternative fuzzy variables have not been studied, it is understood that the behavior obtained when monitoring the variation of power and voltage is satisfactory, with the exception that: it does not have good dynamic performance in abrupt and intense variations of irradiation—see the step from 0 to 1000 W/m^2, have steady oscillations, as a function of the natural oscillation of the convergence process, and lose precision as the irradiation is reduced (all problems al-ready mentioned in the literature).

However, some important observations:

- When keeping at the maximum possible power point, there is a large variation in the boost converter output voltage (200 to 300 V, in the given examples). The output voltage can be kept more constant by using a current inverter to transfer energy to the electrical grid. This step is in its initial stage in this work and, therefore, was not presented.
- Also, if a conventional boost converter is used, the value obtained is not suitable for working with energy injection into the electrical grid without the use of a transformer to adapt the value of the DC link to the appropriate level for a single-phase inverter (approximately 300 V) or three-phase (approximately 400 V). Some adjustments are necessary and, it is suggested, further studies are carried out to determine solutions to the problem.

In summary, it was approached and studied during this work: modeling of photovoltaic modules—analyzing commercial module, modeling of DC-DC converters, boost and boost interval, in the space of average states, fuzzy controller (definition of fuzzy functions and rules)—including simulations in the MATLAB program, and the current inverter modeling was started.

Although the current inverter stage has not been integrated with the final circuit, due to the difficulties encountered, it is suggested that as future works this connection can be carried out and that the MPPT system be connected to the grid. Finally, the results show that even with the irradiation change, the MPPT system is still able to successfully track the MPP.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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