Design and Implementation of a Hybrid Neuro-Fuzzy Corrector for DC Bus Voltage Regulation

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Abstract

The pursuit of the MPP and the control of the inverter play a very important role in a PV system connected to the utility grid. In this paper, an intelligent method is used to regulate the DC bus voltage. The hybrid neuro-fuzzy algorithm HNF type is used. The latter is a combination of fuzzy logic and neural networks. The PV chain, dependent on climatic conditions needs mechanisms to optimize the power it delivers, but also the injection of good quality energy to the utility grid. Among these mechanisms, there is the control of the three-phase inverter: grid currents control and DC bus voltage regulation which is based on the HNF. The implementation of the model and its simulation under Matlab/Simulink indicates that only the active power is injected into the grid. They also reveal that the HNF has a response time (Rt) of 0.097 s, a rise time (rt) of $4.306 \cdot 10^{-3}$ s and a THD of 0.85% compared to the modified PID which has a response time of 0.659 s, a rise time of 0.156 s and a THD of 2.74%.

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1. Introduction

Energy production is a major challenge for the coming years as global energy needs are exponentially evolving. Currently, a large part of the production and the global consumption of energy generates polluting effects or climatic disturbances. The use of fossil resources inevitably reduces the reserves and compromises the energy future of the next generations. As a result, the global challenge is focused on renewable energies (solar, wind, hydro, geothermal, biomass,...) [1].

In recent years, the use of PVS for power generation is recurrent. Most PVS installations are connected to networks. The challenge of this form of use lies both in the optimization of the power produced and the impact in terms of disturbance of the utility grid [2].

The objective of this paper is to propose on the one hand a control technique of the boost converter based on the incremental conductance method for optimized management of the power produced by the photovoltaic generator (PVG). But also, on the other hand, an intelligent technique based on neuro-fuzzy networks will be proposed to regulate the voltage of the DC bus in order to inject good quality energy into the grid.

Indeed, during these last ten years, several methods of pursuit the maximum power point (MPP) have been developed. These methods differ in their implementation, complexity, speed of convergence and efficiency. They are classified in five groups in which we have the usual techniques such as conventional techniques Perturb and Observ (P&O) and Incremental Conductance (InC) and intelligent techniques [3].

The P&O method is widely used. This is largely due to its simplicity of implementation and the non-complexity of its

algorithm. Its principle is based on the search for a better solution based on an arbitrary solution by perturbation of the system. In [4], P&O is used to extract the optimal power in the case of uniform insolation and partial shading by locating the global MPP. The simulation results prove that even for these conditions of shading and uniformity of insolation, the P&O control manages to extract the optimal power in a very short time. The recurring problem with P&O is the permanent disruption of the voltage: this has a negative impact on the power of the system [5].

The InC method, too, is widespread in the literature, mainly due to its ease of implementation and its accuracy. It has the particularity of adapting in a record time to sudden changes in climatic conditions. It is a very efficient conventional technique, using a white box modeling for the extraction of maximum power [6]. The incremental variation can be approximated by the variation of the voltage and current of the PVG at different times. The InC and P&0 methods give almost similar results: the use of these two methods always gives rise to small oscillations around the MPP [7]. Moreover, so-called intelligent methods are becoming more and more frequent in the literature. Their ability to adapt to weather conditions makes them robust controls with very low response times. Artificial Neural Networks (ANN) are known to be very effective because of their great learning ability. Fuzzy logic (FL), it takes advantage of its high descriptive capacity due to linguistic variables. It does not need a priori knowledge to extract the optimal power, but rather variables of the state of inputs and outputs of the system [8], [9]. Thus, the combination of these two techniques offers a good compromise between learning ability and descriptive ability. This is the case of the HNF method. The latter implements a Fuzzy Inference System (FIS) inspired by artificial neural networks. Its use offers the possibility of modeling prior knowledge and linguistic decision rules obtained by experts in the field [10]. Several studies in the literature show that the Adaptive Neuro-Fuzzy Inference System (HNF) method is much more effective than the techniques usually used for MPP research. HNF has a very low response time and fewer oscillations around the MPP than other conventional methods [1]. In this work, the InC method is used for maximum power point tracking (MPPT) controller.

Furthermore, in the case of a PV system connected to the utility grid it is essential to regulate the DC bus voltage [11]. For this, several techniques are adopted. This is mainly the full-wave command, the shifted command and the pulse width modulation (PWM) command since it delivers several slots of suitable width for good filtering of the output voltage or current of the inverter. In this paper, a "hybrid regulation" is proposed: the HNF is used to regulate the DC bus voltage and the modified PID corrector for regulating the current of the three-phase inverter connected to the grid. This regulation will manage the order of opening and closing of the switches so that the DC bus voltage is as close as possible to the reference voltage. It will also inject the compensation currents.

The rest of the article is structured as follows: section 2 presents the modeling of the PVG and the boost converter.

Section 3 presents the work methodology. The section presents the results and discussions. Section 5 presents the conclusion.

2. Modeling of the PV system connected to the utility grid

2.1 Modeling of the PVG

There are several electric models of the cell: model has a one diode, two diodes, and three diodes. The one diode model offers a good compromise between simplicity and precision [12]: it seems very suitable for our study.

The basic equation of the cell does not represent the characteristic of the module. Since the PV modules are composed of several cells, it is necessary to connect the latter in series and in parallel to increase the voltage and the current respectively. Thus, for Ns panels in series and Np in parallel, one has the model of the equation (1):

$$Ipv = Np\left[Iph - Is\left\{\exp\left(\frac{q}{nkT}\left(\frac{Vpv}{Ns} + \frac{RsIpv}{Np}\right) - 1\right)\right\}\right] - \left(\frac{\left(\frac{Vpv}{Ns} + \frac{RsIpv}{Np}\right)}{Rp}\right) \quad (1)$$

Table 1 presents the various parameters of the PVG and the values of the parameters of the conversion chain found with the modeling.

Table 1. Parameters of the PV chain connected to the grid

Parameters	Values
Max PVG voltage	423 V
DC bus voltage	500 V
Max PVG current	14,90 A
Current of charge	7,45 A
Max PVG power	6,44 KW
Boost input capacity	8,62 µF
Boost Inductance	28,99 mH
Boost output capacity	4,31 µF
Load	115,97 Ω
Frequency of switching	10 kHz

2.1 Modeling of the boost converter

The boost converter is a DC-DC converter that allows a higher voltage output than the input. Its use is justified by the fact that the voltage delivered by the PVG is often lower than that desired [13]. It is used first to adopt the voltage levels and secondly to operate the PVG at the MPP. The mathematical modeling of the booster chopper described by the diagram below goes through the analysis of the different operating sequences. A first sequence corresponding to the conduction phase of the power switch (Mosfet) and a second

sequence corresponding to the conduction phase of the diode.

By applying Kirchhoff's laws, we obtain the following equations:

$$V_{pv} = (1 - \alpha)V_{dc} \qquad (2)$$

$$C1 = \frac{I_{pv}}{4F_c \Delta V_{pv}} \qquad (3)$$

$$C2 = \frac{I_{pv}}{4F_c \Delta V_{dc}} \qquad (4)$$

$$L = \frac{V_{dc}}{4F_c \Delta I} \qquad (5)$$

3. Methodology

3.1 MPPT controller

The MPPT controller is based on InC algorithm. It is based on the ratio of the variation of the pressure to the variation of the PVG voltage. At the MPP, the slope is zero. Pursuit is based on the position of the operational point (or slope) (dP/dV) with respect to the MPP [7], [11].

The implementation of the algorithm goes through equations (6) and (7):

$$P_{pv} = I_{pv}V_{pv} \qquad (6)$$

The variation of the power according to the voltage gives:

$$\frac{\Delta P_{pv}}{\Delta V_{pv}} = I_{pv}\frac{\Delta V_{pv}}{\Delta V_{pv}} + V_{pv}\frac{\Delta I_{pv}}{\Delta V_{pv}} = I_{pv} + V_{pv}\frac{\Delta I_{pv}}{\Delta V_{pv}} \qquad (7)$$

The MPP depends on the value of the conductance (I / V). The sign of the latter makes it possible to say whether the MPP is reached or not. It is compared to its incrementation (1 / V). This amounts to saying that the MPP is subject to voltage and current variation (Figure 1).
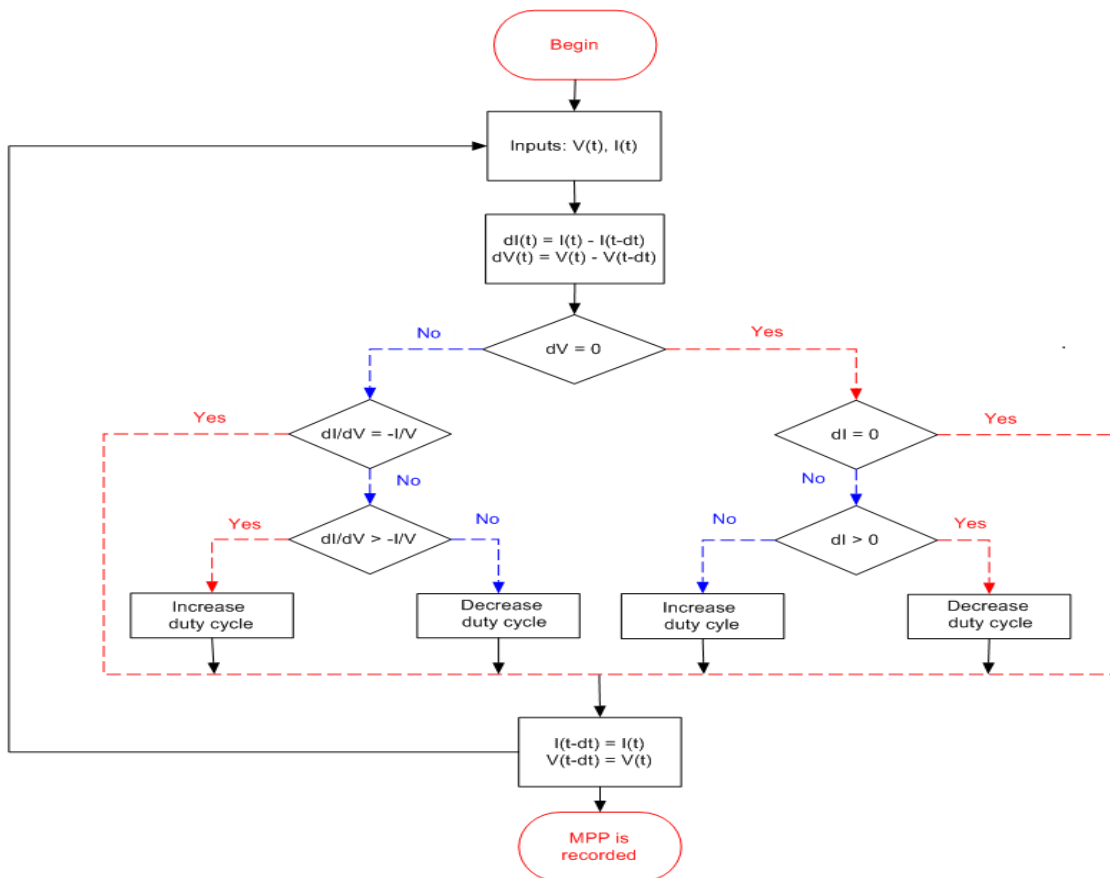

Figure 1. Flowchart of the MPPT technic based on InC

3.2 Control of the three-phase inverter

Inverters are used to interface the distributed generation system (DGS) with the grid, and now because of the continuous research and improved capability of these

devices, the direct integration of the DGS with the grid is increasing. Also, the challenges involved in renewable energy integration are high but can be met with proper designing of the individual components of the integration system. Moreover, the overall performance improvement of the system depends on the operation of each block. Thus, it is required to improve the existing capabilities of the inverter. It should not just act as the power conversion unit that converts DC power to AC power and regulates the power flow, but it should also fulfill the grid regulation and limit the current as per the design. The inverter has the capability to overcome most of the operating challenges that are explained in the previous section. The overcurrent can be limited by designing the inverter control to restrict the current to certain values based on the requirement. In addition, the active and reactive power can be controlled through the inverter control. The active power flow control will reduce the dc-link voltage oscillations which is the weaker link in the inverter system. Thus, it is clear that inverter control is a very critical factor to overcome the existing challenges for the grid-connected system. Three elementary blocs of command around the inverter appear: voltage loop regulation, current loop regulation and phase locked loop (synchronization).

The three-phase inverter is used for high power applications. It is likely to deliver high voltage with low THD [14]. One of the techniques to accomplish this is to use HNF for DC bus voltage regulation and the modified PID (MPID) corrector for current regulation.

3.2.1 DC bus voltage regulation with HNF

Neuro-fuzzy systems are fuzzy systems formed by a learning algorithm inspired by the theory of neural networks. The learning technique operates according to local information and produces only local changes in the system. HNF, a combination of ANN and fuzzy logic, takes advantage of the advantages of both approaches. On the one hand, ANN can improve their transparency, making them closer to fuzzy systems. On the other hand, fuzzy systems self-adapt (automatic setting of parameters), which will make them closer to connectionnary networks (ANN): this justifies their great capacity for process control. The proposed HNF model implements a Takagi Sugeno FIS. It has five layers: the fuzzification layer, the fuzzy rule layer, the normalization layer, the defuzzification layer, and the summation layer. The last layer is the output layer [15].

In this paper, HNF is used for the regulation of the Vdc voltage of the DC bus in the Park base. It is implemented from a database created with a conventional command (modified PID in this case). It is based on the voltage error (difference between the voltage Vdc and its reference) to then generate the reference current from which the current will be regulated with the modified PID: hence a "hybrid regulation". Its first four layers allow it to perform the maximum calculation and verification in a lesser time to generate each time the output corresponding to the input. Learning includes several steps from creating the database to

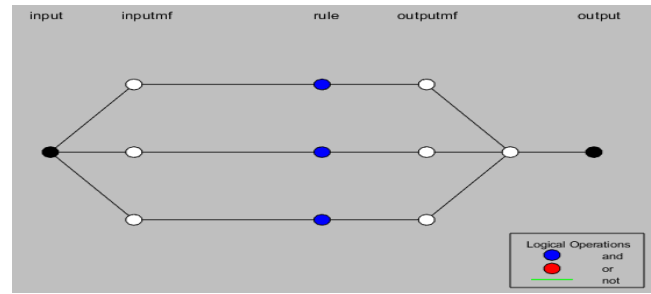verifying the error (Table 2). The structure of HNF is generated with learning (Figure 2).

Figure 2. HNF matlab structure

Table 2. Parameter's values with HNF learning

Parameters	Values
Data base of training	1800
Data base of checking	1200
Number of membership functions	3
Type of membership functions	Gauss, linear
Epochs	100
Error tolerance	0,0001
Training error	0,0023
Checking error	0,0029
Number of fuzzy rules	3

Grid currents regulation with MPID

In contrast to the PID, the modified PID additionally has a high frequency low pass filter at each term. This in order to be more sensitive to noise. This explains its performance compared with other standard proofreaders. In reference [10] for example, it is compared with the PI and the PID. The results show that it is better with a response time of 0.4 s and an overshoot of 2.4%. The PI and the PID respectively (17% and 1.1 s) and (46% and 0.38 s).

It is used here for the regulation of the current. This regulation makes it possible to minimize the harmonic pollution of the three-phase current. Its regulation loop in the Park base is given in figure 3, and table 3 gives the values of its various parameters. Indeed, the regulation of the current is linked to that of the voltage. The reference active current is generated by the voltage regulation loop (HNF) (figure 4).
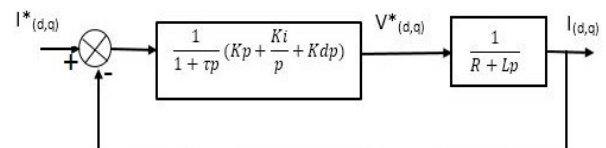

Figure 3. Currents regulation loop

The terms of the MPID corrector are determined using a digital program on matlab (Table 3).

	Output current		
Parameters	K_p	K_i	K_d
Modified PID	0,06	5	$4,12.10^{-4}$

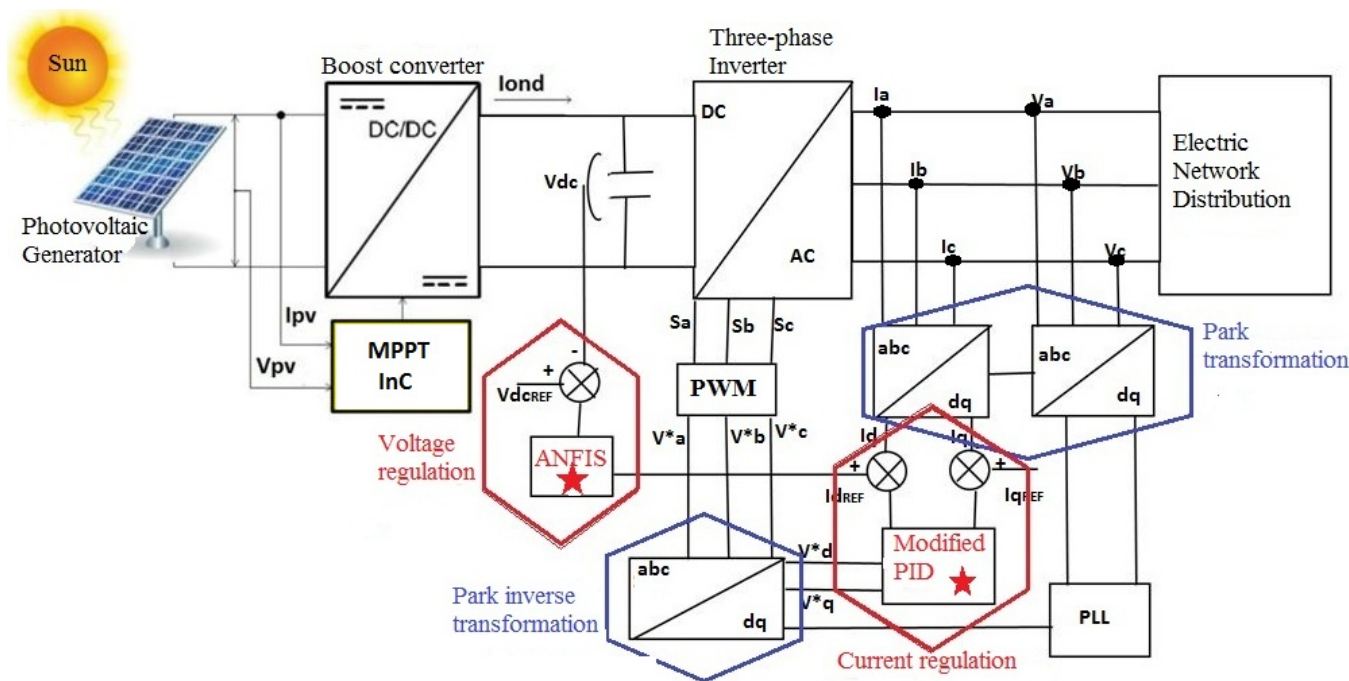Table 3. Values of the modified PID corrector parameters

Figure 4. Diagram of control loops of the three-phase inverter

4. Results and Discussions

In this section, the results of simulations on matlab/simulink are presented.

The model used in this work is composed of a PVG, a boost converter controlled by the InC algorithm, a three-phase inverter associated with a filter, and the utility grid.

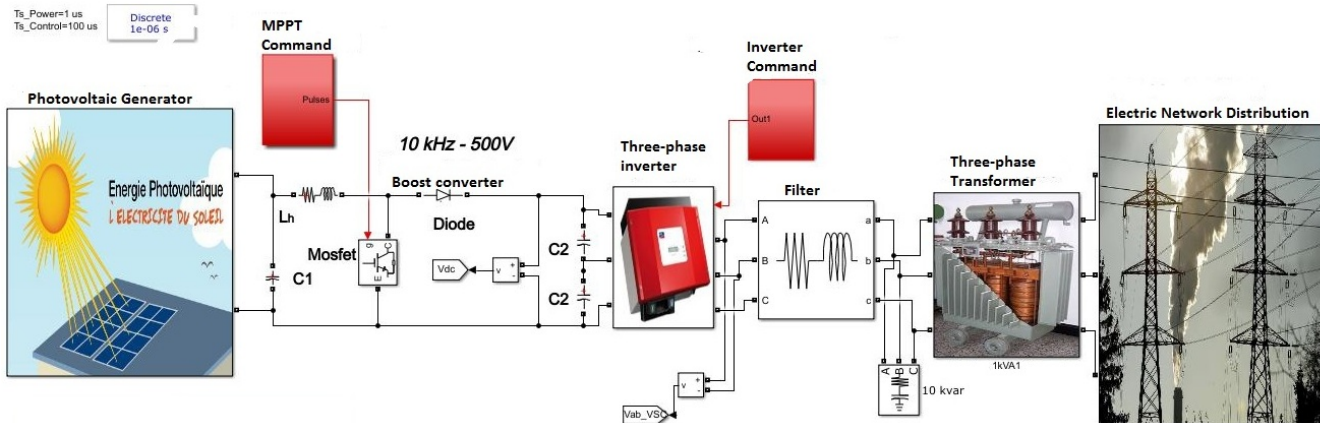The model shown in figure 5 is implemented under Matlab/Simulink.

Figure 5. Studied system implemented under Simulink

Figure 6 represents the voltage loop regulation using HNF. A reference voltage of 500 V is compared to the voltage Vdc. The error obtained is corrected with the HNF corrector. The latter generates the active reference current. The reference reactive current is set to zero. A phase locked loop (PLL) is used to synchronize the output voltage of the inverter to the voltage of the utility grid.
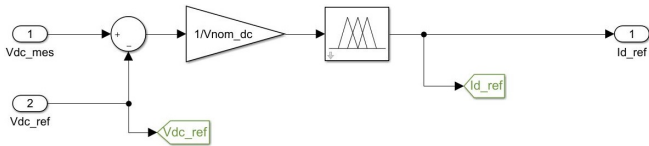

Figure 6. Voltage regulation loop under Simulink

The figure 7 represents the climatic data of solar irradiation and temperature. These two parameters are the most influential on the production of PVG.
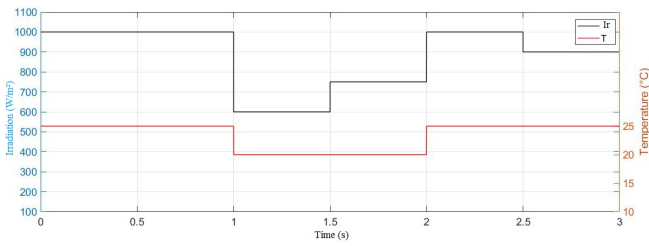

Figure 7. Variation of irradiation and temperature

Figures 8 and 9 show that the active current follows its reference and that the reactive current is almost zero. Figure 11 provides information on the performance of the HNF control for voltage regulation. Compared to the MPID, there is a real difference between the two. HNF has a very short response time (0.097 s) with no overshoot (D) and a very short rise time ($4.306.10^{-3}$ s). While with the MPID, there is an overshoot of 18%, a response time of 0.659 s and a rise time of 0.156 s. Also, from the point of view of precision and stability, the HNF is in front. It follows perfectly the reference at the moment when the MPID oscillates around this same reference. This is justified by the performance and robustness of HNF.

This ability comes from the great learning capacity of neural networks but also from their subordination to the linguistic variables of the FIS. Moreover, the combination of

these two regulators, allowed the injection of a very good quality energy to the grid with a THD of 0.85% on the current respecting the norms (figure 12) contrary to a regulation with MPID where we have a THD of 2.74% (figure 13).

In addition, figure 10 shows the power delivered by the PVG. This is achieved by the MPPT InC command, which allows you to extract at any time the maximum power available despite the weather variations (figure7). This suggests the performance of the InC as MPPT command even if it observes a lag time of 0.5 second before adapting well to climate fluctuations.
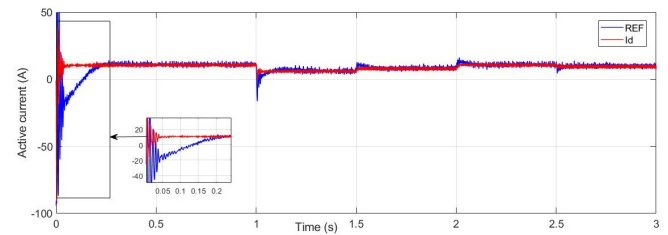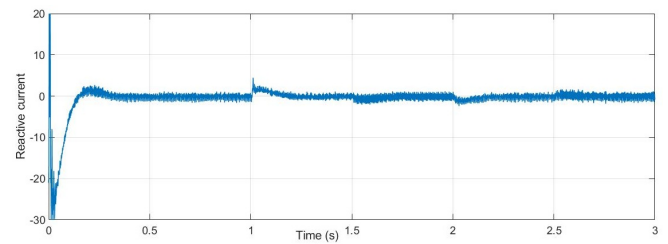

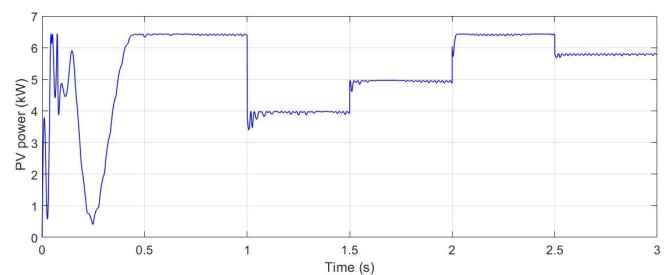**Figure 8.** Active current

Figure 9. Reactive current

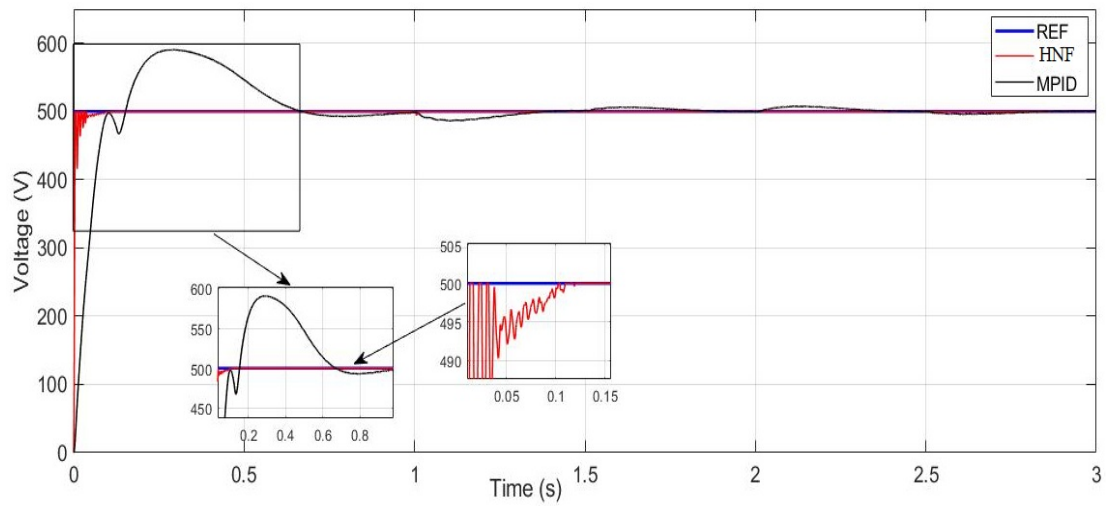**Figure 10.** PVG power with InC MPPT command

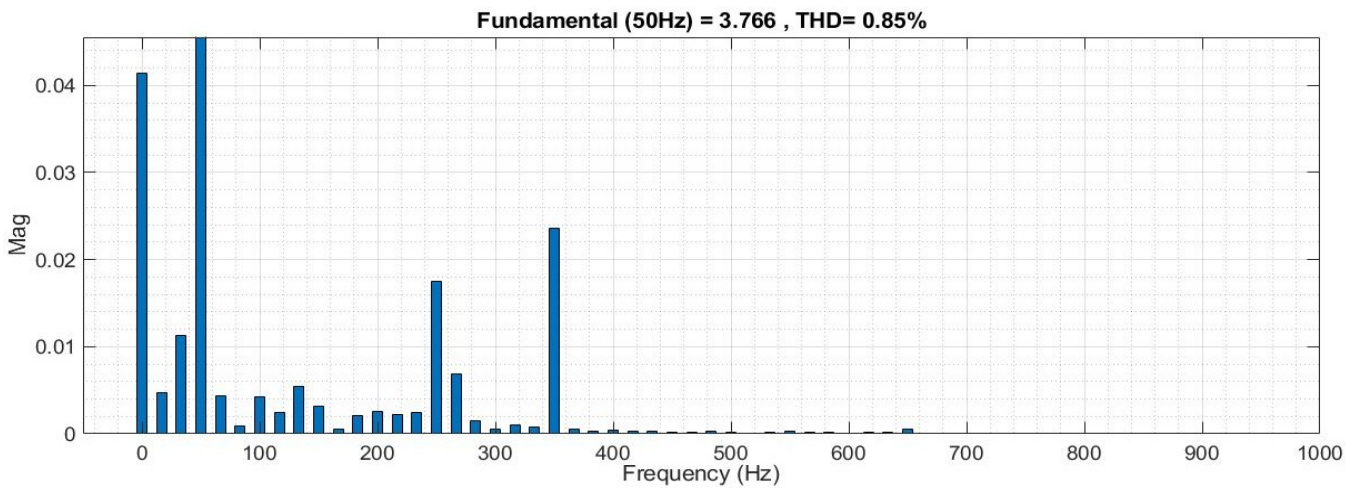**Figure 11.** DC bus voltage with HNF and MPID correctors

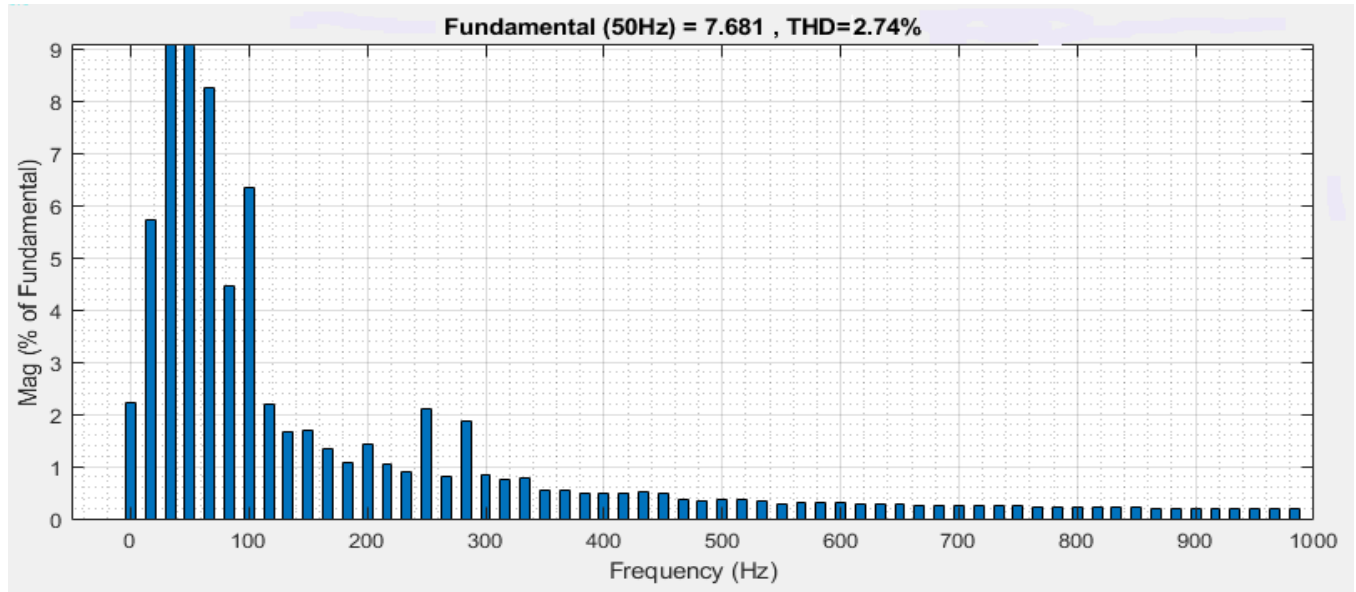**Figure 12.** THD on the current with HNF

Figure 13. THD on the current with MPID

Table 4 shows the results of the simulation. It highlights the performance and robustness of the HNF by comparing it with the MPID. In reality, HNF adapts itself to climatic fluctuations and even to momentary technological drifts such as the dissipation of energy by certain devices.

5. Conclusion

The convergence towards renewable energies justifies our choice for PV systems connected to the grid. These systems use converters to connect to the utility grid and the power injected is highly variable since it is dependent on the irradiation and the temperature. The work presented in this paper consisted of the use of control techniques of the three-phase inverter to ensure a good injection to the grid. Hence the use of HNF to regulate the DC bus voltage and the MPID to regulate the grid currents. The results obtained show a quality injection, but also the performance of the DC link control. Compared with the MPID which is better than the other classic proofreaders, we realize that HNF is more robust and more efficient. However, its implementation remains difficult and very boring. This is especially related to the choice of the database and its learning.

Table 4. Performance and robustness parameters

	Vdc voltage			
Criteria	Rt (s)	rt (s)	D(%)	THD (%)
HNF	0,097	$4,306.10^{-3}$	0	0,85
MPID	0,659	0,156	18	2,25

Notations	Meanings	Notations	Meanings	Notations	Meanings
ANFIS	Adaptive Neuro Fuzzy Inference System	P&O	Perturb and Observ	C1	Boost input capacity
PVS	Photovoltaic Solar	PVG	Photovoltaic Generator	C2	Boost output capacity
MPP	Maximum Power Point	THD	Total Harmonic Distorsion	Vdc	DC link voltage
InC	Incrementale Conductance	FIS	Fuzzy Inference System	Fc	Frequency of switching the Mosfet
PID	Proportional Integral Derivative	PCU	Power Conditioning Unit	α	Duty cycle
HNF	Hybrid Neuro Fuzzy	T	Operating temperature of the cell	L	Inductance
Vpv	PV voltage	Ipv	PV current	P	Variable of Laplace

Is	Saturation current	Iph	Photo current	Kp	Proportional gain
n	Ideality factor of the diode	q	Charge of the electron	Ki	Integral gain
Rs	Serie resistance of the cell	Rp	Parallel resistance of the cell	Kd	Derivative gain
K	Boltzmann constant	R	Inverter filter resistance	τ	Constant time
Ia, Ib, Ic	Output inverter current	Va, Vb, Vc	Simple voltages of the inverter	Sa, Sb, Sc	Switching states of the inverter
Vd,q	Active and reactive voltage	Id,Iq	Active and reactive current	PWM	Pulse Width Modulation

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