Experimental Validation Under dSPACE of the ANN-PID Control of the DC Link for Injection of Solar Energy to the Grid

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Abstract- In this paper, the main objective is to make an experimental validation of the adaptive Proportional Integral Derivative based on Artificial Neural Network (PID-ANN). This technique used for regulating the DC link voltage of a photovoltaic Three Phase DC-AC Converter (3P-DC-A2C) connected to the grid. The mathematical model of the DC link is presented. Applications under Matlab / Simulink justify the efficiency of the neural regulator. In comparison with the conventional method, the proposed method presents the best follow-up of the DC link voltage reference. It respectively ensures a maximum overshoot and a quadratic error of 0.54 % and 1.0279 against 15.90 % and 3.7631 of classical one. In add, using the neural method as DC link voltage regulator, Total Harmonic Distortion (THD) in current is improved (2.27 % against 2.45 %). These simulation results of the DC link voltage are proven by those experimental ones where one finds the best follow-up of the DC link reference voltage with an optimal precision using the neural PID than the classical PID. A response time of 10 ms is also obtained against 55 ms of the classical PID. With a brutal change, the proposed method proves its robustness and stability.

Keywords PID-ANN, DC link, 3P-DC-A2C, THD, Photovoltaic, Grid.

1. Introduction

Today, the main concern of many countries is how to meet the current energy demand with less pollution. This is virtually assured by fossil fuels which are exhaustible and the cause of global warming by the Greenhouse Gases emissions (GHGs) [1-3]. Following this awareness, researchers find it necessary to focus on alternative energies in order to ensure environmental protection and an adequate supply of energy [4-7]. These energies are inexhaustible on human scale, less polluting [4, 8]. Solar photovoltaic (PV), able to meet some of the current energy needs, have a very important potential for development in Senegal [9]. Thus, with the n˚2010-21 law on the framework law on renewable energy, Senegal can benefit a significant portion of the electrical energy from PV system. This will be crucial for the success of its new model of development that is the Emergent Plan of Senegal (EPS). Photovoltaic Solar systems (PV2S) connected to the grid, become a development technology because they can help to reduce the GHG and meets current energy demand. Despite all advantages, this phenomenon remains complex and effected by means of static electronic power converters (DC / DC and DC-A2C). Furthermore, the intermittent character of PV source remains the main problem when connected to the grid [10, 11]. This one gives rise to variations in the DC link voltage. These variations negatively affect the 3P-DC-A2C’s performance [12, 13]. The DC link voltage is also disrupted in the case of saturation of the injected current (voltage drop or short circuit in the 3P-DC-A2C output) [8]. In case of short circuit, the grid voltage drop and mains a decrease of the injected power to the grid while the power supplied by the PV generator remains constant [14]. This imbalance causes an increase in the DC link energy stored which is originally sometimes of the overshoot voltage across the capacitor to the allowable limits [15]. After elimination of the fault, the DC link voltage stabilizes with a higher value. The 3P-DC-A2C part in the influence of the quality of electrical energy injected by a significant THD in current but also the overall performance of the system by a large number of switching losses and conduction (due to transistor type properties). This scenario leads to the goal where the work is registered in this paper. This is the proposition of a control based artificial neural

networks (ANN) for controlling the DC link voltage to improve the 3P-DC-A2C performances. However, the 3P-DC-A2C occupies an essential place in the PV2S connected to the grid while altering the quality of energy but also the system global performance. These disadvantages show that improving their performances always remain a sought goal.
It is in this perspective that a classical Proportional Integral (PI) is used to regulate the DC-link voltage in order to reduce fluctuations and grid current harmonics within a tolerable limit. Simulation results, proved by the experimental results, show the effectiveness of the proposed technique [16]. In [17], a modified PID is used for regulating the DC link voltage and output current of the 3P-DC-A2C in the Park's base. The results show a best following of the DC link voltage reference. The stability of the DC link voltage in a PV2S connected to the grid is improved by the use of a modified linear active disturbance rejection control [18]. The theoretical applications and those experimental proved the robustness of the proposed method. In [19], the authors use a fractional order proportional integral (FOPI) for controlling the voltage. This regulation balances the reactive power and ensures a unit power factor and low THD. An adaptive PI controller regulates the DC voltage of a 3P-DC-A2C. Results, compared to the conventional technique, show that voltage fluctuations are reduced of 68 % and rapidity is improved [20, 21]. The simple use of PI controller pushed authors toward a comparative study of meta-heuristic techniques [22]. These methods determine the optimal gain of PI regulator which enables to answer objective like increasing 3P-DC-A2C efficiency, stability, unit power factor and low THD. However, the obtained results attained through Matlab-Simulink prove that the whales optimization algorithm technique is best than others studied meta-heuristic techniques in terms of 3P-DC-A2C efficiency, stability, power factor and THD. Because of the performance and simplicity, the hysteresis controllers are largely used as a direct control current of a 3P-DC-A2C with a PI for controlling the DC link voltage [23, 24]. This technique present a good response time in regulation of the DC link [24].

The quality of the injected energy is improved by the intervention of intelligent techniques which play a very important role. The hybrid control neuro-fuzzy, which is the combination between ANN and the fuzzy logic, gave a best response time and a precision [25]. In add, an energy quality of a THD of 3.02 % is injected to the grid. The ANN and the radial basis function neural networks generate the best PI parameters for controlling the output current of 3P-DC-A2C and to solve the problems of active and reactive powers [26, 27]. The first one, in comparison with the classical hysteresis control, gives the best form of injected currents proven by a THD of 1.4 %. In [28], PI based on predictive NN controller is used to improve performances of the 3P-DC-A2C. Using the predictive controller and the approximate dynamic programming based on ANN, the simulation results gave respectively an optimal power factor and a THD of 0.66 % [29]. In [30], the proportional resonant regulator ensures a THD of 3.83 %.

At the end of our literature review, we have not met an author used the neural PID for regulating the DC link of a 3P-DC-A2C. Furthermore, the conversion chain of a PV2S remains the same, only the control techniques are improved [7]. In this study, an adaptive PID based on ANN is used for regulating the DC link voltage. This method allows achieving a supple injection at unity power factor to the grid. For this, it will minimize the influences due to climatic changes, voltage dip or short circuits at the 3P-DC-A2C output. The proposed method also overcomes the limitations of classic PID by improving response time and possibly overshoots.

2. Proposed Technics for Controlling the DC Link

2.1. DC Link

The DC link allows to storage energy but also to filter voltage fluctuations due to switching. Despite these advantages, its voltage is sometime perturbed by climatic changes through variations in the output current of the DC converter which is the PV current image. Its constancy improves the 3P-DC-A2C performances. The regulation will minimize influences due to climatic variations on the DC link voltage. The temporal and Laplace current flowing through the DC link are respectively given to as Eq. (1) and Eq. (2).

$$dV_{dc} = (I_{dc}/C_{dc})\, dt \tag{1}$$

$$H(s) = V_{dc}(s)/I_{dc}(s) = 1/sC_{dc} \tag{2}$$

Where V_{dc} represents the DC voltage in (V), I_{dc} represents the DC current in (A), C_{dc} represents capacitor in (F) and s is Laplace variable.

2.2. Regulation of the DC Link Voltage

The DC link regulation is made using an adaptive PID based on ANN. This technic is the combination between the classical PID regulator and the ANN.

- *Proportional Integral Derivative (PID)*

The PID is an industry regulator. With the derivative term, it improves the system stability. The transfer function of such a regulator is described to as Eq. (3). The regulation loop is given in Fig. 1.

$$C(s) = k_{dc} + (k_i/s) + (sk_d/1+s\tau) \tag{3}$$

Where k_p, k_i and k_d are respectively proportional, integral and derivative gain. τ is the constant time.

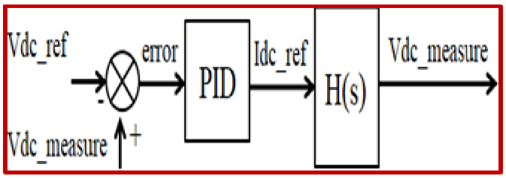

Fig. 1. Structure of classical PID control loop.

- *ANN-PID Controller*

As defined previously, the neural PID is the combination between the ANN and the conventional PID controller. The

ANN, made of three layers (input layer, a hidden layer, and an output layer) [31], is used to adjust the PID parameters. This improvement is made using the back propagation of the gradient descent through the error function Y (k). This function is defined to as Eq. (4). This learning algorithm adjusts synaptic weights (X_{ij}) as showed to as Eq. (5).

$$Y(k) = 1/2(V_{dcref}(k) - V_{dcmeasure}(k))^2 \tag{4}$$

$$X_{ij}(k+1) = X_{ij}(k) - \beta(\partial Y(k)/\partial X_{ij}(k+1)) + \alpha Y(k-1) \tag{5}$$

Where Y is the cost function, V_{dcref} is the reference DC voltage in (V), $V_{dcmeasure}$ is measured DC voltage in (V), α is momentum factor and β is learning rate.

The structure of this technique and its flowchart are respectively illustrated in Fig. 2 and Fig. 3.

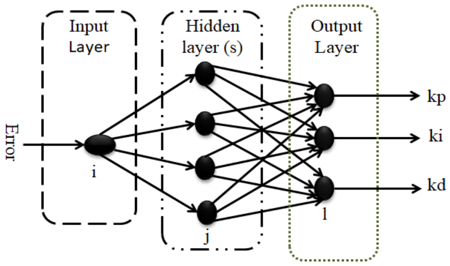

Fig. 2. Structure of ANN-PID controller

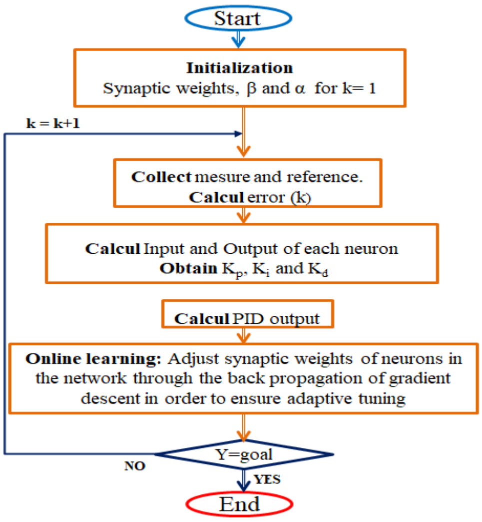

Fig. 3. Flow chart of the neural PID

The transfer function used to activate hidden layers and the output layer neurons are respectively the sigmoid M(μ) and hyperbolic tangent T(μ). These functions are given to as Eq. (6) and Eq. (7).

$$M(\mu) = 1/1 + \exp(-\mu) \tag{6}$$

$$T(\mu) = 1/2(1 + \tanh(-\mu)) \tag{7}$$

Where M is the sigmoid function and T is hyperbolic tangent function.

In summary, the implemented global control scheme under Matlab / Simulink environment is given in Fig. 4.

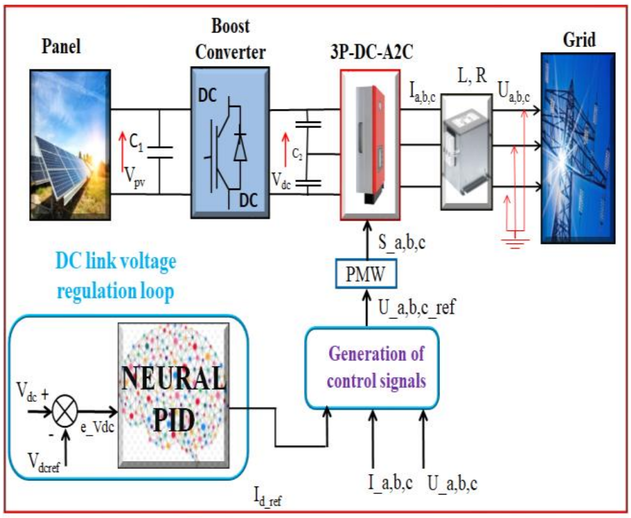

Fig. 4. Global scheme of the control PV2S connected to the grid

3. Simulation Results and Discussions

The behavior study of the proposed method is carried out under the environment Matlab/Simulink. For this, the controlled system is simulated using the variation climates shown in Fig. 5. In the context of this paper, the irradiation and temperature profiles are used.

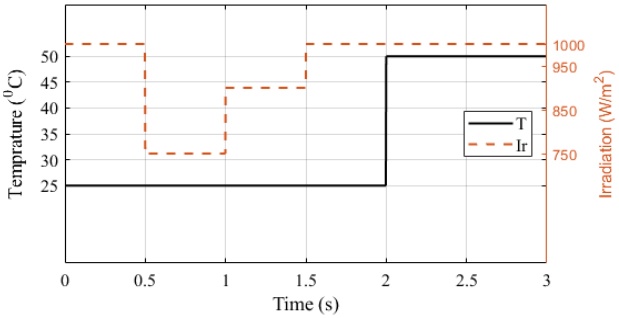

Fig. 5. Irradiation and temperature profile

The applications carried out allowed us to record the curves of Fig. 6. These curves represent the DC link voltage using the conventional and the neural PID. This figure shows that the neural PID ensures the best effectiveness and robustness. It presents an overshoot of 0.54 % in transient regime against 15.90 % of classical one. The both technique almost present no static error in permanent regime.

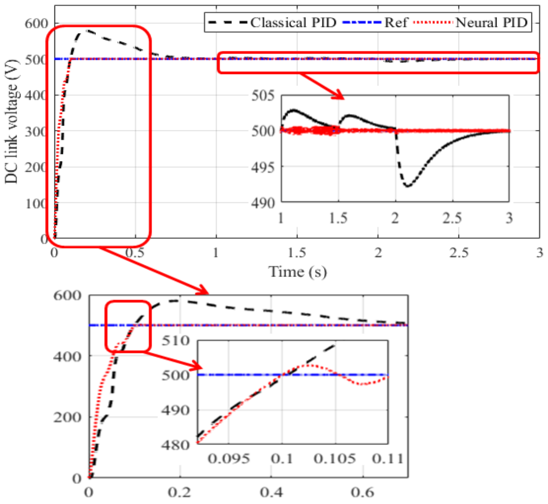

Fig. 6. DC link voltage of the PV system

The difference between the conventional and neural PID is clarified by a comparative study based on errors as quadratic error (RMSE) which allows to study the precision, absolute error in percent (MAPE) and absolute error (MAE)), and overshoot (O) and response time (Rt). The results are showed in Fig. 7.

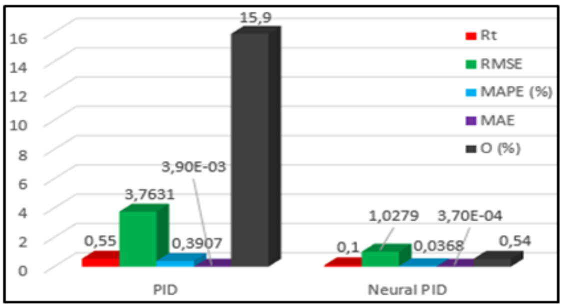

Fig. 7. Diagram of the simulation statistic variables

However, the results from the grid side are represented by the injected currents and presented in Fig. 8. These curves are obtained by the use of the classical regulator PID in the Park transformation. The results presented in Fig. 9 and 10 prove that the 3P-DC-A2C gave the best energy quality using the neural method as DC link voltage regulator unlike conventional PID. In add of the quality, the power factor operation or a single injection of active power is showed by the curves of Fig. 11 where the injected current of one phase and the grid voltage are in phase.

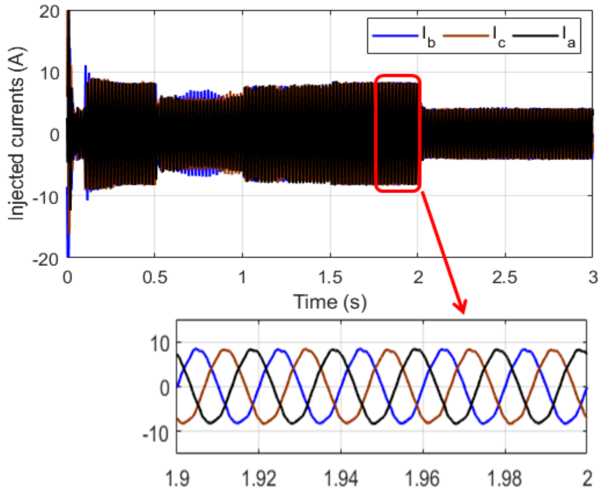

Fig. 8. Injected currents of PV2S

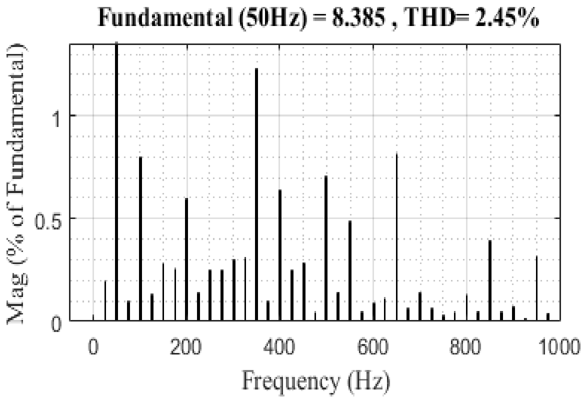

Fig. 9. THD of the injected currents using classical PID

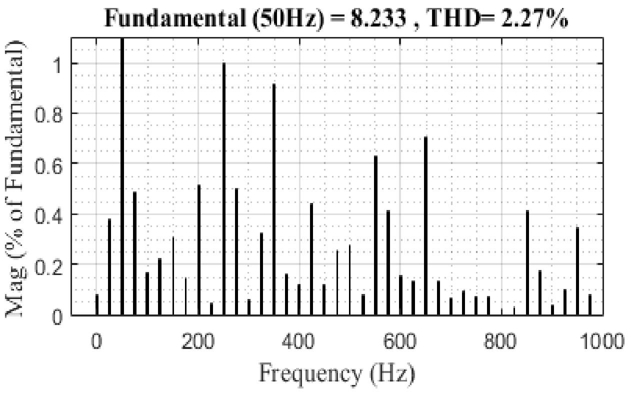

Fig. 10. THD of the injected currents using ANN-PID

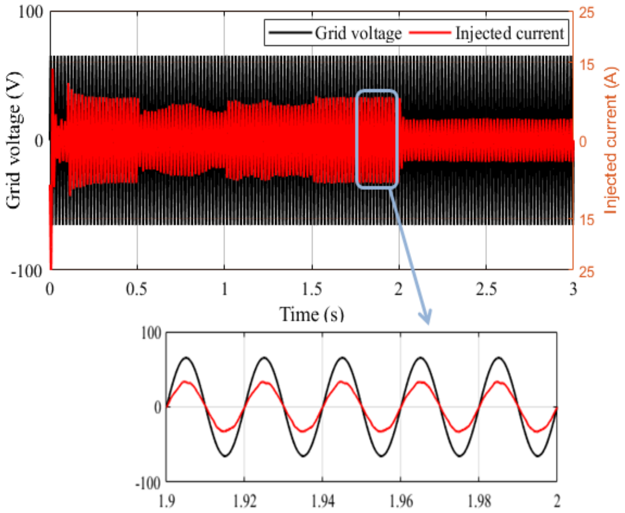

Fig. 11. PV injected current phase and grid voltage

4. Experimental Validation

4.1. Presentation of the Experimental Bench

To make the experimental validation of the proposed model, a test bench of the CERTES laboratory at Paris East Creteil University, France was used. This experimental bench is in Fig. 12. The DC/DC converter is composed of IGBT modules, switched at 10 kHz, with a common capacitive connection of 840 µF. The function of the latter is to smooth the voltage at the terminals of the 120 Ω DC load. Moreover, the charging current DC is filtered by an inductance of 1 mH. A neural PID is implemented under a dSPACE 1202 Microlabbo Real Time Interface (RTI). The connection between the dSPACE board and the DC/DC power converter is performed by an electronic interface board, which adjusts the signal level control to the IGBT voltage. The sensors (LA25NP) and (LV25P) respectively obtain the different currents and the voltages.

The Simulink model used on dSPACE during experimental validation at CERTES laboratory is showed in Fig. 13.

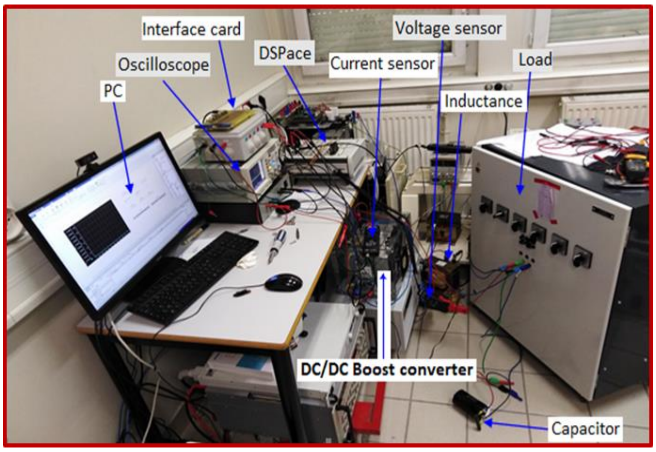

Fig. 12. Used experimental setup

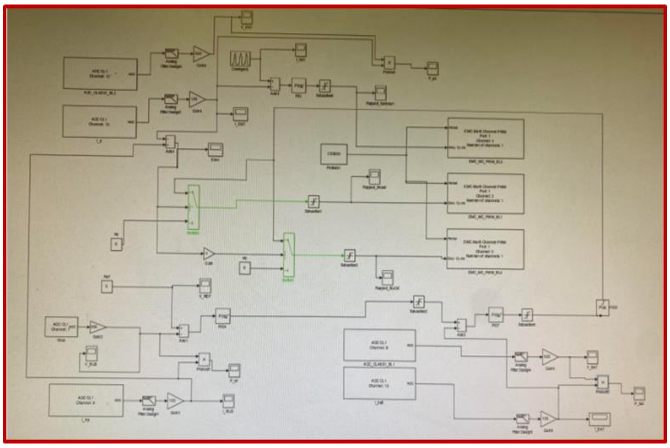

Fig. 13. Simulink model implementation on dSPACE

4.2. Performance Study

To study the performance of the neural PID regulator, we are focused on the following criteria of the rapidity and error like RMSE, MAPE and MAE. The obtained results over [0; 210 s], superposed on theoretical results, are in Fig. 14. Experimental statistic variables in terms of errors and response time are in Fig. 15.

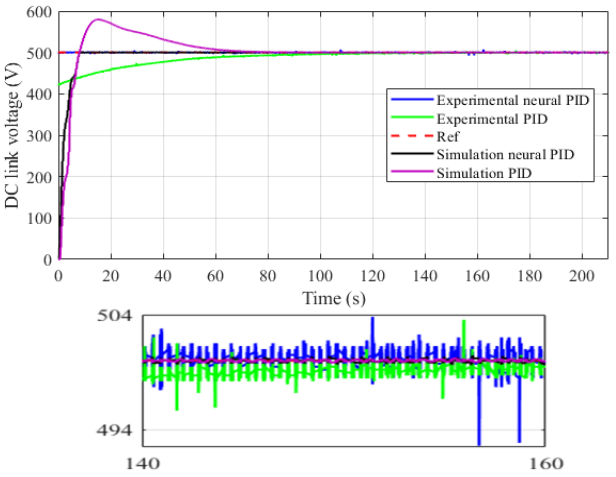

Fig. 14. Simulation and experimental DC link voltage

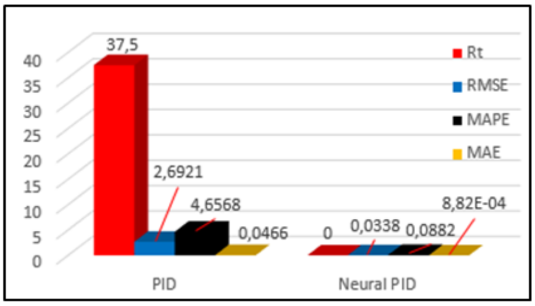

Fig. 15. Diagram of the experimental statistic variables

Based on the results of Fig. 15, we can prove the rapidity of the neural method, in comparison with the classical technique, by a zero response time against 37.5 s of the classical PID. In addition to the latter, better precision is obtained with the use of the proposed technique. This superiority is justified by the RMSE because the method is precise the lower the RMSE. These results prove those of the simulation.

4.3. Robustness Study

To study the robustness of the proposed method, a variable reference voltage (with a brutal change) is applied to the systems. The obtained results using classical and neural method are respectively illustrated in Fig. 16 and Fig. 17.

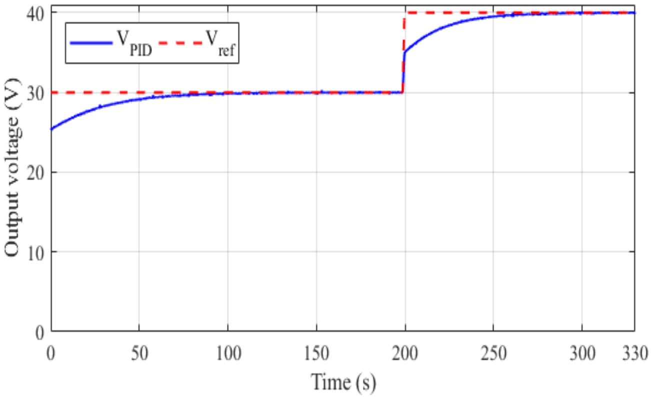

Fig. 16. Experimental DC link voltage using classical PID

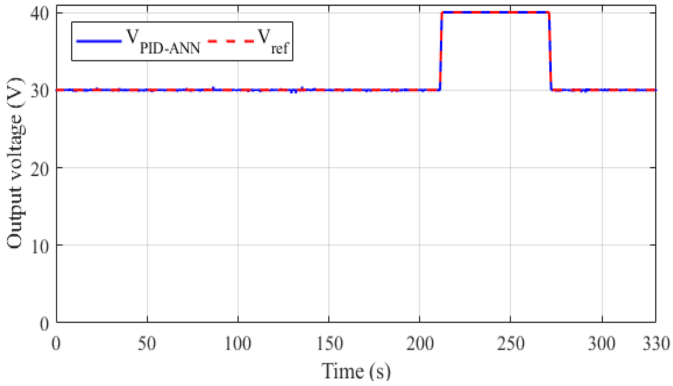

Fig. 17. Experimental DC link voltage using PID-ANN

Figure 17 proves the robustness of the neural PID by a good following of the reference voltage with regard to the disturbances of the latter. Unlike in Fig. 16 where this followed is observed after a transient passage of an average response time of 50 s. This delay, not observed with the neural method, characterizes power losses. Moreover, these results demonstrate the stability and robustness of the neural method.

5. Conclusion

The neural PID has been used in this paper for regulating the DC link voltage. This regulation improves 3P-DC-A2C performances supplied by a PV2S. Results show that the neural PID ensures the best effectiveness and robustness. It presents an overshoot of 0.54 % in transient regime compared to 15.90 % of classical one. The presented response time of the ANN-PID is 0.1 s against 0.55 s of the classical PID. In add, the best injected currents are obtained using the neural controller (THD of 2.27 %) compared to the classical PID regulator (THD of 2.27 %).

In addition to the theoretical study, a made experimental study validated the proposed method. The latter confirms performances and robustness of the neuronal PID regulator like the simulation results.

Despite the performance of the proposed method, the implementation of artificial intelligence in particular ANN remains a complex process. Thus there are key parameters that can affect the learning mechanism of the ANN in order to decrease their performance. However, the structure of the ANN obviously the number of hidden layer also their numbers of neurons must be automated or perfectly determined

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