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Design and Simulation of Grid-Connected Photovoltaic Single-Phase Inverters

Gabriel Roméo Tobajio Haoudou [1], Arnaud Biyobo Obono [2], Léandre Nneme Nneme [3], Jean Mbihi [4]

[1] Research Laboratory of Computer Science Engineering and Automation, University of Douala, PB: 1872 Douala, Cameroon, rtobajio@yahoo.fr
[2] Research Laboratory of Computer Science Engineering and Automation, University of Douala, PB: 1872 Douala, Cameroon, obonobiyo@yahoo.fr
[3] Research Laboratory of Computer Science Engineering and Automation, University of Douala, PB: 1872 Douala, Cameroon, leandren@gmail.com
[4] Research Laboratory of Computer Science Engineering and Automation, University of Douala, PB: 1872 Douala, Cameroon, mbihidr@yahoo.fr

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ABSTRACT

This paper focuses on a new control strategy for single-phase photovoltaic inverters connected to the electrical power distribution network. The inverter studied is single-phase H bridge, equipped with a robust control strategy by sinusoidal duty cycle modulation.

This new control strategy offers the advantage over the control strategy. Most used control in its first approximation (PWM control technique): A low Hardware complexity; a variable modulation frequency/period; a topology of modulation with feedback. This inverter structure is further composed of the robust PI controllers, a boost chopper and an LCL filter. The low voltage electrical network to which this inverter is connected is materialized and simulated by a voltage source of characteristics 230V-15A-50Hz and synchronized to the latter by a phase-locked loop (PLL). In this article, the main components of the grid-connected PV power plant are modeled and simulated under Matlab/Simulink as well as the simulation of the global behavior of the entire network+PV inverter and the results obtained are presented.

Key words: Photovoltaic inverter, Sinusoidal duty cycle modulation, robust controller, PLL, Virtual simulation

1. INTRODUCTION

In recent decades, the global challenge has been to develop renewable energy sources, including solar, wind, hydro, etc. These sources are not only free and inexhaustible, but also environmentally benign. These sources are not only free and inexhaustible, but also environmentally friendly [1]. Despite the fact that energy production depends on sunshine (which is always variable), the very high cost and the low conversion efficiency, the photovoltaic market is growing at a considerable rate [2]. This growth is leading to the development of low power [3].These sources are usually equipped with storage systems, such as accumulators, which make it possible to compensate for the intermittent nature of the production and thus to be able to react promptly and efficiently to demand depending on the time of day. However, the inclusion of many decentralized sources in the grid leads to many problems, the most important of which are grid stability and the quality of the power available at the common connection point [3, 4]. It is then necessary to properly design the inverter serving as the electrical interface from the source to the grid, and especially to optimally select and size its control to ensure a good interconnection to the distribution grid [5]. Although the PWM control technique is generally the most used in the control of these inverters, the new sinusoidal duty cycle modulation control technique, given its advantages [7- 22], also allows us to develop new prototypes of reliable inverters with performances comparable to that driven by pulse width modulation developed [23].

2. METHODS AND TOOLS

2.1. General structure of the single-phase grid-connected inverter with sinusoidal duty cycle modulation control

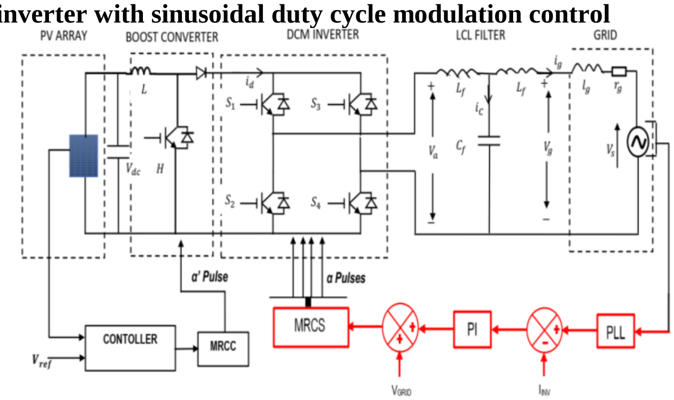

Figure 1: General synoptic

2.1.1. Photovoltaic panels

The photovoltaic panels used for the study and simulation are those of 1SOLTECH 1STH-215-P, also having the above characteristics

Table 1: PV field parameters

Elements	Characteristics
PV array	10 parallels et 4 series
Irradiance/Temperature	1000W/m^2 ; 25°C
PV current	16,50A
PV voltage	182V
PV power	3KW

2.1.2. Boost chopper

The structure of the chopper used in this work remains the same as that used in the context of autonomous photovoltaic single-phase inverters with SDCM control and therefore the characteristics are recalled below: Vin=182V, α=0.5,Vout= 364V.

2.1.3. Optimal duty cycle modulator

The analog power flow model of the duty cycle modulator is given in figure 2 below:

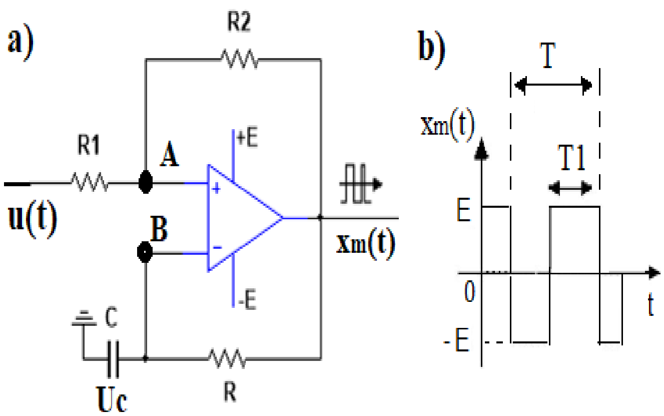

Figure 2: Electrical diagram of DCM

Sizing this modulator in duty cycle amounts to determining the values of the passive components R, R_1, R_2 and C.

These values depend on the base frequency (F_{mo}) of the modulator in duty cycle and the latter is obtained by imposing the value of the modulating signal at zero (u=0) in equation (1).

$$T = RCln\left[\frac{\left(2\frac{R_1}{R_2}+1\right)^2-\left(\frac{u}{E}\right)^2}{1-\left(\frac{u}{E}\right)^2}\right] \qquad (1)$$

$$F_{m0} = \frac{1}{T_0}$$

$$F_{m0} = \frac{1}{2RC\ln\left(2\frac{R_1}{R_2}+1\right)} \qquad (2)$$

This sizing approach allows obtaining the parameters of the modulator in duty cycle but with a wide range of trial and error, hence the welcome of an optimization algorithm of the parameters of the modulator in duty cycle synthesized by equation (3) [2].

$$\begin{cases} \alpha^* = Max_{\alpha}\left(p_m(\alpha) = \dfrac{\alpha}{E(1+\alpha)\ln\left(\dfrac{1+\alpha}{1-\alpha}\right)}\right) \\ \quad with \\ f_{m0}(\alpha) = \dfrac{1}{2\tau\ln\left(\dfrac{1+\alpha}{1-\alpha}\right)} \\ f_{\min}(u_{\max},\alpha) = \dfrac{1}{\tau\ln\left(\dfrac{((1-\alpha)u_{\max})^2-((1-\alpha)\mathrm{E})^2}{((1-\alpha)u_{\max})^2-((\alpha-1)\mathrm{E})^2}\right)} \\ 0<\alpha<1 \end{cases} \qquad (3)$$

The optimal parameters obtained and presented in Table 2 below of the duty cycle modulator, were determined with the fmincom optimization tool from matlab in accordance with the cost function stated in equation (3).

Table 2: Optimal duty cycle modulator settings

	Elements used	Simulation parameters	Electronic parameters
Duty cycle modu lator	f_{m0} = 1 Mhz E=5V X_{max}=4V	α = 0.857142857142857 α_2 =1- α= 0.14285714285 τ=RC= 1.7380297483*10^{-06}	R=1.5kΩ ; C=1.1587nF R_1=10kΩ ; R_2=60kΩ Slew rate = 1000V/us

2.1.4. Phase Locked Loop (PLL)

In order to synchronize the output current of the inverter with the grid voltage in order to give a clean sinusoidal current reference, a classic PLL is used for this purpose and therefore the structure is shown in Figure 3 below:

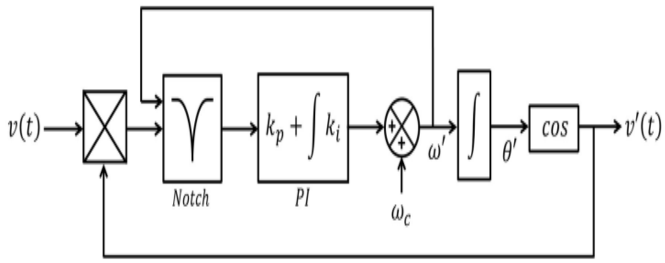

Figure 3: Structure of the PLL used

The model in the form of a block diagram is then presented in Figure 4.

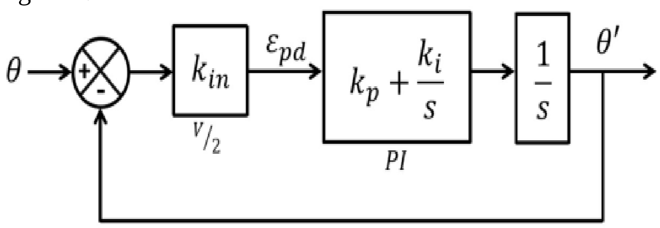

Figure 4: Block diagram of the linearized system

This functional diagram is translated into a transfer function and given by the standard form:

$$H_{PPL}(s) = \frac{2\xi\omega_n.s+\omega_n^2}{s^2+2\xi\omega_n.s+\omega_n^2} \qquad (4)$$

with

$$\begin{cases} k_p = \dfrac{2\xi\omega_n}{k_{in}} \\ k_i = \dfrac{\omega_n^2}{k_{in}} \end{cases} \quad \text{or} \quad \begin{cases} \xi = \dfrac{k_{in}k_p}{2\sqrt{k_{in}k_i}} \\ \omega_n = \sqrt{k_{in}k_i} \end{cases} \qquad (5)$$

Table 3: Table of values

f_{min}(Hz)	f_c(Hz)	f(Hz)	K_P	K_I
45	25	50	180	3200

2.1.5. LCL harmonic filter

Its important in filtering the switching frequency and the surrounding frequencies. The rectangular voltage at the output of the bridge corresponds to the voltage v_a, while v_s is the voltage at the output of the total system, connected to the PCC. The best alternative is the LCL filter. The LCL third-order low-pass filter, placed at the output of the bridge, offers good attenuation even with low values of $L_{1,2}$ and C, as well as low output current ripple despite its complex structure.

2.1.5.1. Frequency analysis of the LCL filter

The open loop transfer function of the LCL filter in Laplace space is written:

$$F_{LCL}(p)\big|_{V_g=0} = \frac{I_g(p)}{V_a(p)} = \frac{Z_C}{Z_C\left(Z_{L1}+Z_{L2}\right)+Z_{L1}Z_{L2}} \qquad (6)$$

By replacing the different elements by their expression in Laplace's symbolic space, we obtain equation 7.

$$F_{LCL}(p)\big|_{V_g=0} = \frac{1}{p(L_1+L_2)+p^3(C.L_1\cdot L_2)} \qquad (7)$$

The frequency analysis of this transfer function leads us to the Bode diagram, whose amplitude and phase are given in figure 5 below**:**

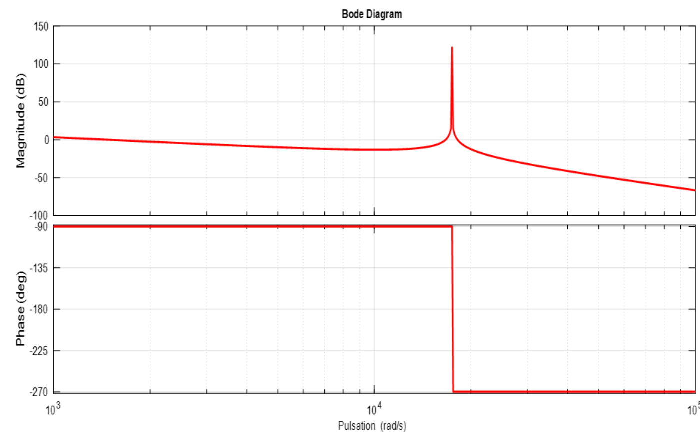

Figure 5: Bode Diagram in BO of the system

2.1.5.2. Characterization of the output filter

In order to avoid resonance and instability problems, it is recommended to maintain this resonance frequency between 10 times the line frequency (50Hz), and half the switching frequency of the inverter:

$$F_{rés,LCL} \in \left[10\, f_s, \frac{f_d}{2}\right] \Rightarrow F_{rés,LC} \in [0.5\ ;12.5]\, khz \qquad (8)$$

Its resonant frequency is given by:

$$F_{rés,LCL} = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{C.L_1\cdot L_2}} \quad \text{AN: } F_{rés,LCL} = 2.77 khz \in [0.5\ ;12.5]\text{khz} \qquad (9)$$

Table 4: Table of values

Elements	Characteristics
L_1, r	700µH, 1mΩ
L_2, r	200µH, 1mΩ
C, r	42µH, 1mΩ
F_{reso}	812 khz

2.1.5.3. Closed loop stability

The Bode Rivers Criterion therefore applied to the asymptotic Bode diagram of Figure 5 leads to the conclusion that the closed-loop system is unstable. Hence the need for a control law for stabilizing the current/voltage quantities at the common connection point.

3. RESULTS OBTAINED AND DISCUSSIONS

3.1. Virtual simulation platform and structure

Matlab's Simulink environment is the platform used to perform the virtual simulations on the inverter prototype presented in this work [24].

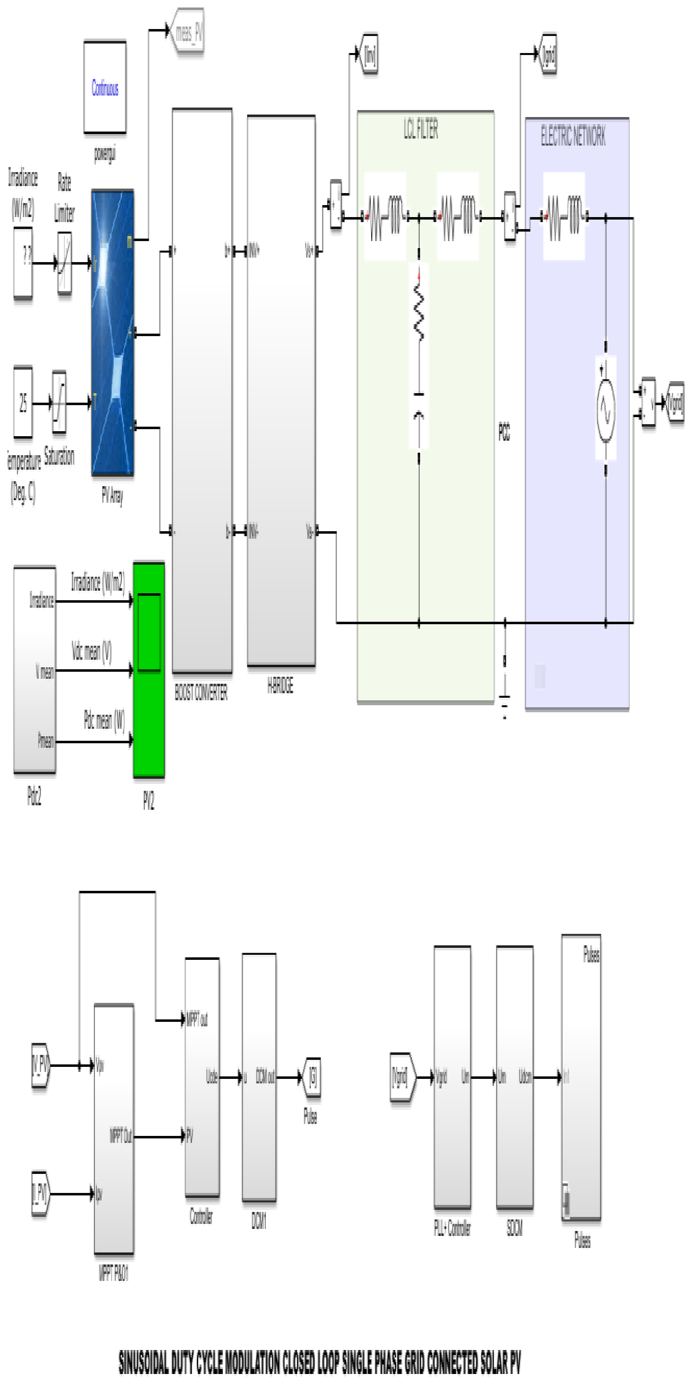

Figure 5: Simulink structure of the autonomous PV inverter with DCM control

3.2. Results of simulations and discussions

3.2.1. Current and voltage at the output of the PV array

The current and voltage characteristics as a function of time at the output of the photovoltaic field are those of figure 6 below. It can be seen that the PV array delivers a constant current of 16.5A under a constant DC voltage of 182V.

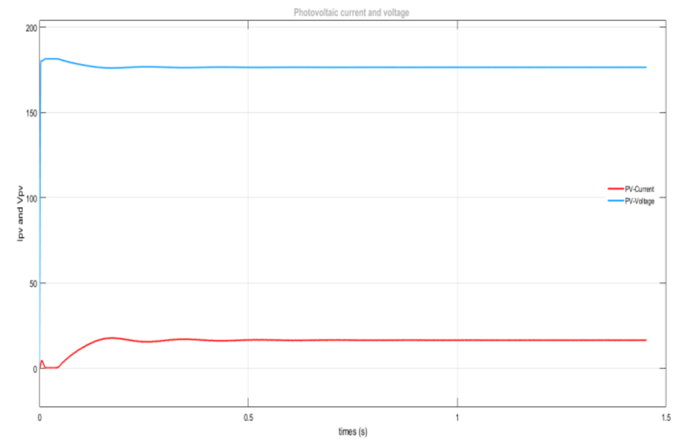

Figure 6: PV array current and voltage

3.2.2. Voltage at the output of the boost chopper

The voltage at the input of the bridge is 364V, corresponding to a voltage at the input of the BOOST chopper of 182V under a duty cycle α'=0.5. We clearly see in the figure below that the output voltage of the parallel chopper increases and stabilizes at the output value of 364V.

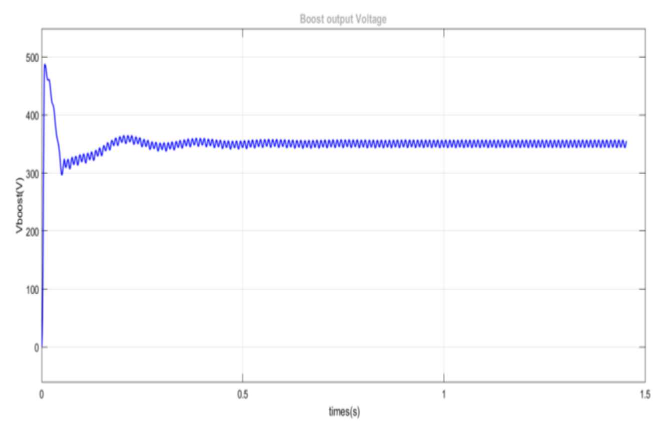

Figure 6: Voltage at the output of the boost chopper

3.2.3. Voltage and current at the output of the inverter

Are respectively given in blue and red in Figure 7, the voltage and the current at the output of the H-bridge.

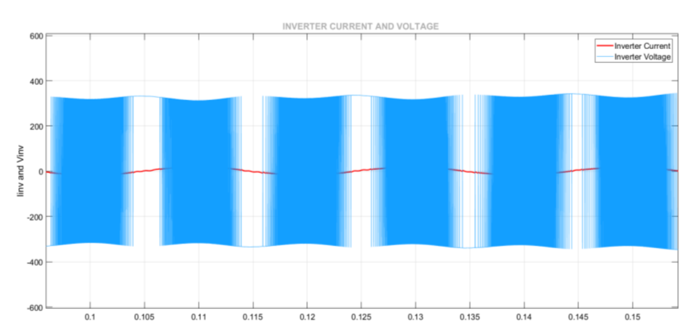

Figure 7: Voltage and current at the output of the inverter

3.2.4. Harmonic spectrum of the voltage at the output of the inverter

Figure 8 below shows the evolution of the harmonics in the steady state signal. We can see that the harmonic distortion rate is very disastrous, that is to say an overall rate of THD = 106.91%.

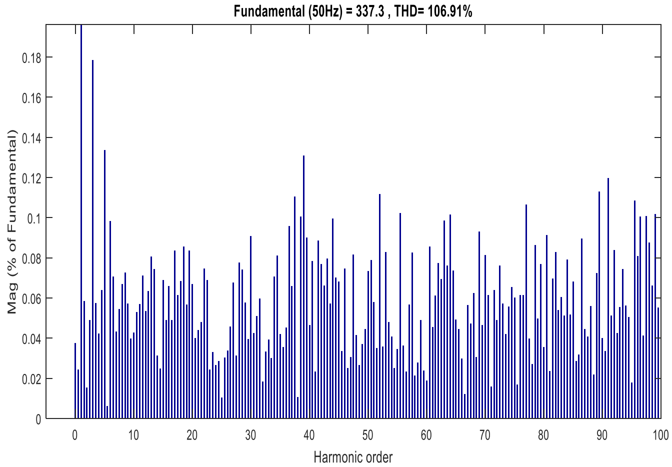

Figure 8: Harmonic spectrum of the voltage at the output of the inverter

3.2.5. Harmonic spectrum of the current at the output of the PV inverter

It can be seen that the overall current harmonic distortion rate at the output of the inverter is 10.76%.THD not acceptable according to the EN50160 standard.

Figure 9: Harmonic spectrum of the current at the output of the inverter

3.2.6. Mains voltage and current

The electrical network is modeled and simulated by a source of characteristics: V_{res}=230V, I_{res}=14A, f=50Hz

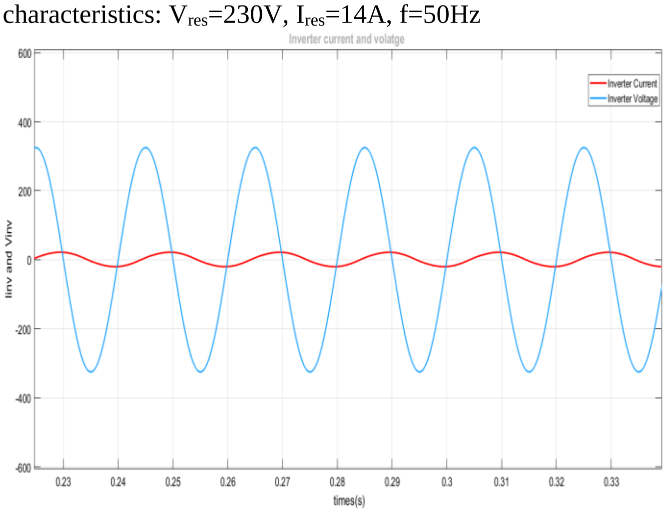

Figure 10: Voltage at common connection points

3.2.7. Evolution of the source voltage harmonic distortion rate

It can be seen that outside the system start-up phase, the overall voltage harmonic distortion rate is 0.00%. THD acceptable according to standard EN50160

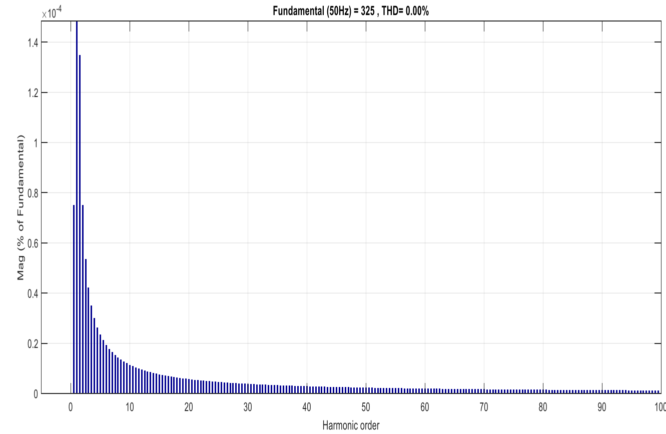

Figure 11: Harmonic spectrum of the voltage at the common connection points

3.2.8. Current harmonic distortion rate

It can be seen that the source current harmonic distortion rate is 2.07%.THD acceptable according to standard EN50160.

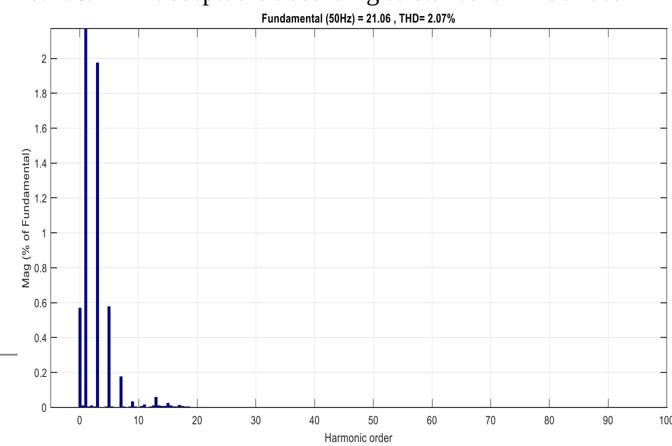

Figure 12: Harmonic spectrum of current at the common connection points

4. CONCLUSION

This study presents a new principle of control of single-phase PV inverters connected to the electrical distribution network using a phase-locked loop. The inverter structure, whose originality is essentially based on its control strategy (control by modulation in duty cycle) and equipped with an LCL output filter, presents an inexpensive and easy-to-monitor architecture. It also allows simple and quick maintenance. The general structure, modeling and simulation of the grid-connected PV inverter are presented as well as the virtual simulation results in the Matlab/Simulink platform.

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