

Optimization design of single phase inverter connected to the grid

Linda Hassaine * and Mohamed Rida Bengourina

Centre de Développement des Energies Renouvelables, CDER
B.P. 62, Route de l'Observatoire, 16340 Bouzaréah, Algiers, Algeria

(reçu le 18 Juin 2019 - accepté le 30 Juin 2019)

Abstract - *In grid-connected photovoltaic systems significant improvements can be carried out in the design and implementation of inverters: reduction of harmonic distortion, elimination of the DC component injected into the grid and the proposed control. This paper proposes a control strategy based on PWM switching patterns for an inverter for photovoltaic system connected to the grid in order to control the injected current. The current injected must be sinusoidal with reduced harmonic distortion. An additional filter is designed to reduce high-order harmonics on the output side. This strategy exhibits the advantages: Simplicity, reduction of harmonics, size of the line filter, reduction of the memory requirements and power calculation for the control.*

Résumé - *Dans les systèmes photovoltaïques raccordés au réseau, des améliorations significatives peuvent être apportées à la conception et à la mise en œuvre des onduleurs, réduction de la distorsion harmonique, élimination de la composante DC injectée dans le réseau et de la commande proposée. Cet article propose une stratégie de commande basée sur des schémas de commutation PWM pour un onduleur d'installation photovoltaïque connecté au réseau afin de contrôler le courant injecté. Le courant injecté doit être sinusoïdal avec une distorsion harmonique réduite. Un filtre supplémentaire est conçu pour réduire les harmoniques d'ordre supérieur du côté de la sortie. Cette stratégie présente des avantages, simplicité, réduction des harmoniques, taille du filtre de ligne, réduction des besoins en mémoire et calcul de puissance pour le contrôle.*

Keywords: Control - Inverters - LCL Filter - Grid connected photovoltaic system.

1. INTRODUCTION

Generally, the single phase inverter is used for low power of PV system connected to the grid.

The grid-connected PV systems extract maximum power from the PV arrays. The Maximum power point tracking (MPPT) technique is usually associated with a DC-DC converter. The DC-AC converter injects sinusoidal current into the grid with a reduced harmonic distortion [1-5].

The harmonics caused by the switching of the power conversion devices are the main factor-causing problems to sensitive equipment or the connected loads, especially for applications above several kilowatts, where the price of filters and total harmonics distortion (THD) is also an important consideration in the systems design phase.

The inductance of the input or output circuits of the power conversion devices have conventionally been used to reduce these harmonics. However, as the capacity of the systems have been increasing, high values of inductances are needed, so that realizing practical filters has been becoming even more difficult due to the price rises and the poor dynamic responses [1].

An L filter or LCL filter is usually placed between the inverter and the grid to attenuate the switching frequency harmonics produced by the grid-connected inverter.

* l.hassaine@cder.dz

Compared with L filter, LCL filter has better attenuation capacity of high-order harmonics and better dynamic characteristic [6-7]. However, an LCL filter can cause stability problems due to the undesired resonance caused by zero impedance at certain frequencies.

To avoid this resonance from contaminating the system, several damping techniques have been proposed. One way is to incorporate a physical passive element, such as, a resistor in series with the filter capacitor [6].

This passive damping solution is very simple and highly reliable. However, the additional resistor results in power loss and weakens the attenuation ability of the LCL filter. This drawback can be overcome by employing active damping [5].

2. PROPOSED PV INVERTER SYSTEM

Figure 1 shows the photovoltaic system connected to the grid. The main objective, from this interfacing, is to feed all the collected energy at the PV plant to the AC grid.

- PV array transform the sun light to electricity.
- MPPT controller, this is used to maximise the power coming from PV array at any atmospheric conditions.
- Inverter, this is a device which transform DC input to an AC output at the same waveforms as the grid line.

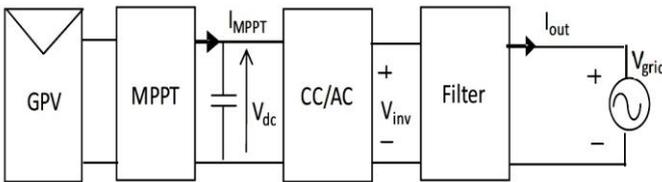


Fig. 1. PV system connected to the grid

3. PROPOSED CONTROL STRUCTURE

The implemented control structure for the single-phase inverter is shown in figure 2. The photovoltaic system consists in photovoltaic generator (PVG), a maximum power point tracking (MPPT) and a single-phase inverter.

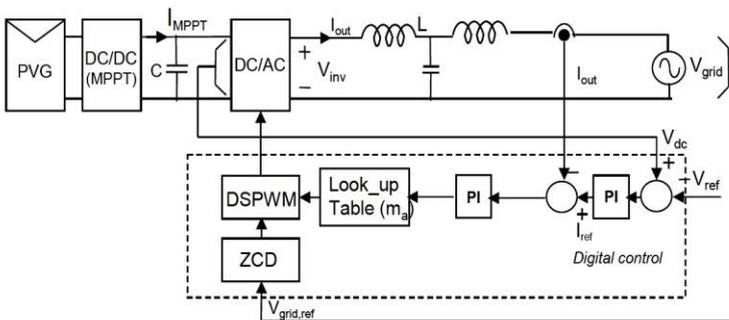


Fig. 2: Control structure for a single phase inverter

The structure of the propose control is a power control based on the use of PWM patterns previously calculated and stored in the look up table for different amplitudes indexes modulation (m_a).

This proposed method have a possibility to adjust automatically a new PWM pattern when the m_a change. The represented diagram corresponds with two control loops: an internal one, that allos controlling the inverter output current and an external one that controls the DC bus voltage V_{dc} .

The proposed control is that the output current I_{out} is controlled by varying the amplitude modulation index m_a . The Digital Pulse-Width-Modulator (DPWM) converts the stored code in the look up table in pulsating signal and generates the driving signals of the switches. The duty cycle depends on the stored code for each pattern defined by m_a . The synchronization of the I_{out} and the V_{grid} is assumed with the zero crossing detectors (ZCD).

The synchro-signal starts the shifted phase counter. Initially is loaded from the look up table to the phase register the code corresponding with the actual value of the phase according with a PWM patterns that satisfy the output current reference.

4. MODULATION - SINUSOIDAL PWM

In most situations a sinusoidal output voltage is required. This may be achieved by modulating the pulse width of each bridge leg using a sine wave reference. A typical scheme compares the value of a fixed frequency triangle wave with a reference sine wave to produce the PWM control signal. (figure 3).

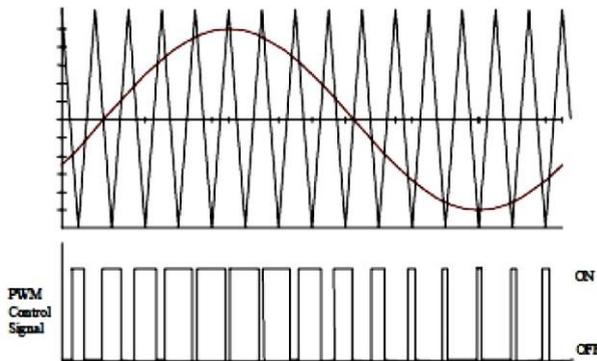


Fig. 3: Sine-Triangle PWM

There are two common switching strategies, which are applied to the H-Bridge inverter; these are Bipolar and Unipolar PWM switching.

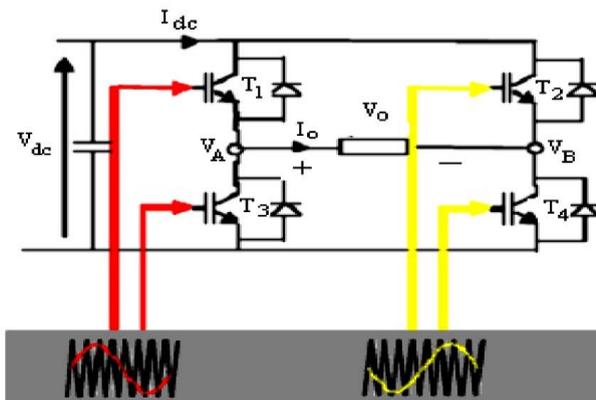


Fig. 4: Single Phase Full Bridge: Unipolar Switching

Unipolar PWM involves switching legs A and B of an H-Bridge separately. In unipolar switching, leg A is controlled by comparing V_{tri} triangle with $V_{control}$ whilst leg B is controlled by comparing V_{tri} triangle with $-V_{control}$ (figure 4).

The effect of this switching strategy on the behavior of the semiconductor switches in the H-bridge is as follows.

Leg A

- $V_{control} > V_{tri}$ T1 ON,
- $V_{control} < V_{tri}$ T4 ON

Leg B

- $-V_{control} > V_{tri}$ T3 ON,
- $-V_{control} < V_{tri}$ T2 ON

The resulting waveform from this PWM scheme is shown in figure 5. As this diagram shows the output voltage switches between 0 and V_{dc} , or, between 0 and $-V_{dc}$. This is in contrast to the bipolar switching strategy in which the output swings between V_{dc} and $-V_{dc}$. As a result, the change in output voltage at each switching event is halved in the unipolar case from $2V_{dc}$ to V_{dc} .

The effective switching frequency ‘seen’ by the load is doubled and the voltage pulse amplitude is halved. Due to this, the harmonic content of the output voltage waveform is reduced compared to bipolar switching.

It is also the periods of zero voltage in Unipolar PWM switching which lend themselves to the idea of auto calibrating a DC link current sensor for the purpose of eliminating DC current injection.

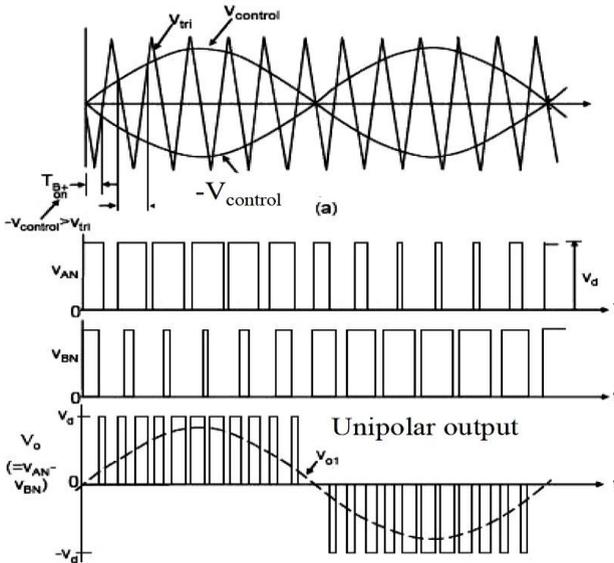


Fig. 5: Unipolar PWM Switching Waveforms

5. PROPOSED PWM METHOD

The proposed method is based on the use of the PWM switching patterns of the inverter output voltage V_{inv} shown in figure 4. To control each one of the transistor, in the proposed method, the transistors commute only in one half-cycle with a double frequency (figure 6).

The single-phase inverter has been simulated, using the PWM pattern calculated a priori. In figure 4, the proposed PWM used for transistor commutation is realized as:

$$V_{g1} = 1, V_{g4} = PWM, V_{g2} = \overline{PWM}, V_{g3} = 0$$

$$V_{g2} = 1, V_{g3} = PWM, V_{g4} = \overline{PWM}, V_{g1} = 0$$

From figure 5, it can be deduced that the obtained inverter output voltage is the same of the inverter voltage in figure 6.

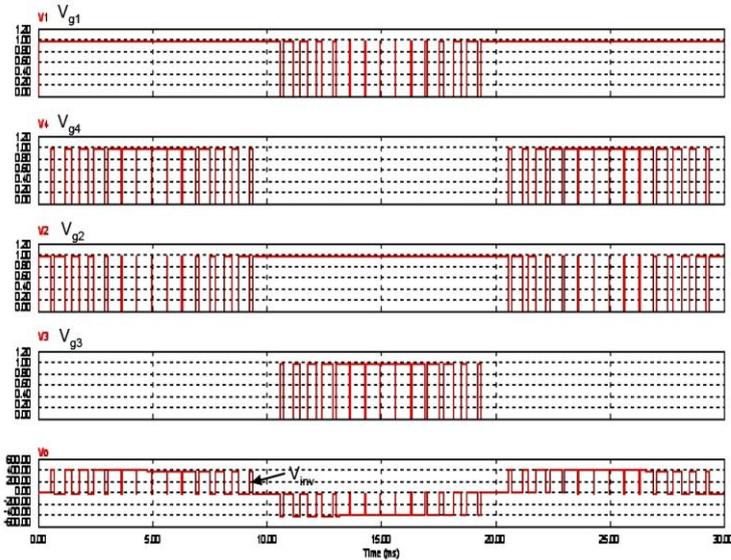


Fig. 6: Proposed PWM pattern

The spectrum frequency of the inverter output voltage is shown in figure 7.

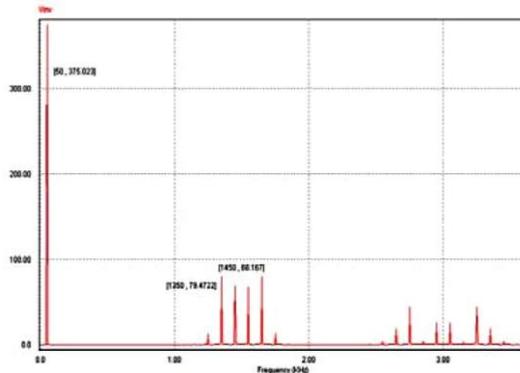


Fig. 7: Voltage spectrum frequency

The choice of inductance grid connection influences the harmonic content of the current injected into the grid and the maximum active and reactive power that the inverter can deliver to the grid.

High inductances lead to reduced harmonic distortion. However increasing the inductance in the filtrate shows a number of drawbacks: cost reduction and transfer of power inverter.

L filter is a first order filter, therefore, the switching frequency of the converter must be high to obtain a high attenuation of the harmonics caused by the PWM with a reasonable size of the inductances.

The LCL filter offers the possibility in reducing the harmonics caused by the switching of the converter with reduced values of the inductance, compared to the L-filter case. LCL filter disadvantages with respect to filter L are: the choice of the components is more complicated besides the control algorithms [8-10]

To analyse the behaviour of this control strategy for single-phase inverter connected to the grid via an L or LCL filter. It has been using the expression of power factor mentioned in {Eq (1)} [2]

$$PF = \cos \varphi = \frac{m_a \cdot V_{dc}}{\omega L \cdot I_{out}} \cdot \sin \delta \tag{1}$$

To measure the distortion of the output current, the total harmonic distortion, THD is often used. Total Harmonic Distortion is a measure of the proportionality between the fundamental and the sum of all other frequencies in the current waveform. {Eq. (2)} defines the THD used here

$$THD_i = \frac{\sqrt{I_{out}^2 - I_{out1}^2}}{I_{out1}} \tag{2}$$

Where I_{out} is the total current; RMS is the Root means square and I_{out1} is the fundamental current (RMS).

The relationship between the switching frequency f_c and the inductance value of output filter is presented, assuming a power factor $PF = 0.996$.

In **Table 1** some values of the inductance value according to the frequency modulation index are summarized.

Table 1. Relationship between switching frequency and inductance value of L and LCL filter, $PF = 0.996$

f_c	L	L1	L2	L1+L2
1.5	2	20	4.5	12.5
2.2	8	3	1.5	4.5
3	3	1.8	0.72	2.52
5	1.43	1	0.55	1.55
9	0.74	0.98	0.7	1.68
10	0.69	0.86	0.4	1.26
12	0.56	0.68	0.3	0.98
15	0.45	0.52	0.25	0.77
20	0.325	0.36	0.2	0.56

Comparing in figure 8, the simulation results of the inverter connected to the grid via an L filter and an LCL filter.

Assuming a $PF = 0.996$, it can be conclude that for lower switching frequencies (modulation indexes for low frequencies) less than 5kHz, the inductance value of the L filter is higher than the value of the inductance ($L1 + L2$) of the LCL filter.

Also, for a $PF = 0.95$, it has been determined inductances values for the L filter and LCL filter as reported in **Table 2**.

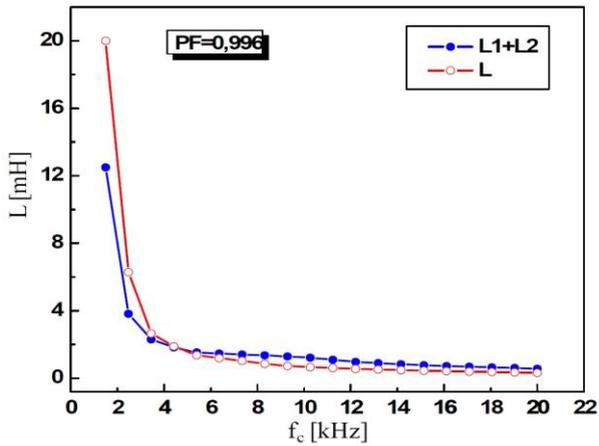


Fig. 8: Inductance of L filter and LCL filter as function of switching frequency f_c , for PF = 0.996

Table 2. Relationship between switching frequency and inductance value of LCL filter PF = 0.95

f_c	L	L1	L2	L1+L2
1.5	1.3	1	0.5	1.5
2.2	0.85	0.6	0.26	0.86
3	0.6	0.56	0.23	0.79
5	0.36	0.4	0.2	0.6
9	0.1025	0.12	0.09	0.21
10	0.094	0.115	0.065	0.18
12	0.08	0.075	0.065	0.14
15	0.07	0.06	0.038	0.098
20	0.05	0.04	0.02	0.06

It can be conclude, when the switching frequency is superior to 5 kHz, the value of the inductances (L1 + L2) of the LCL filter is higher (practically double) than the inductance value of the filter L.

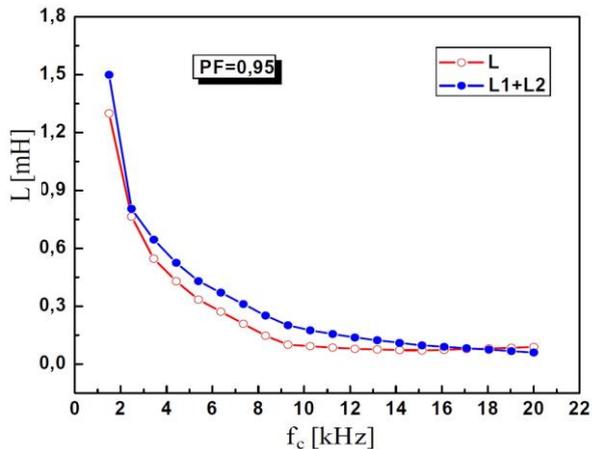


Fig. 9: Inductance of L filter and LCL filter as function of switching frequency f_c , PF = 0.95

The LCL filter has good current ripple attenuation even with small inductance values. However, it can bring also resonances and unstable states into the system. The Bode plots of the LCL filter without and with damping are shown in figure 10.

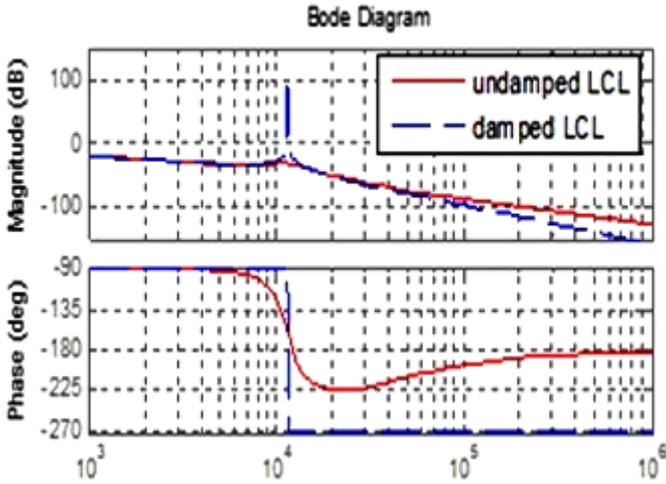


Fig. 10: Bode diagram of LCL Filter

6. SIMULATION RESULTS

The Photovoltaic system connected to the grid have been simulated by PSIM figure 11. The Simulation results of the photovoltaic system connected to the grid are presented in following:

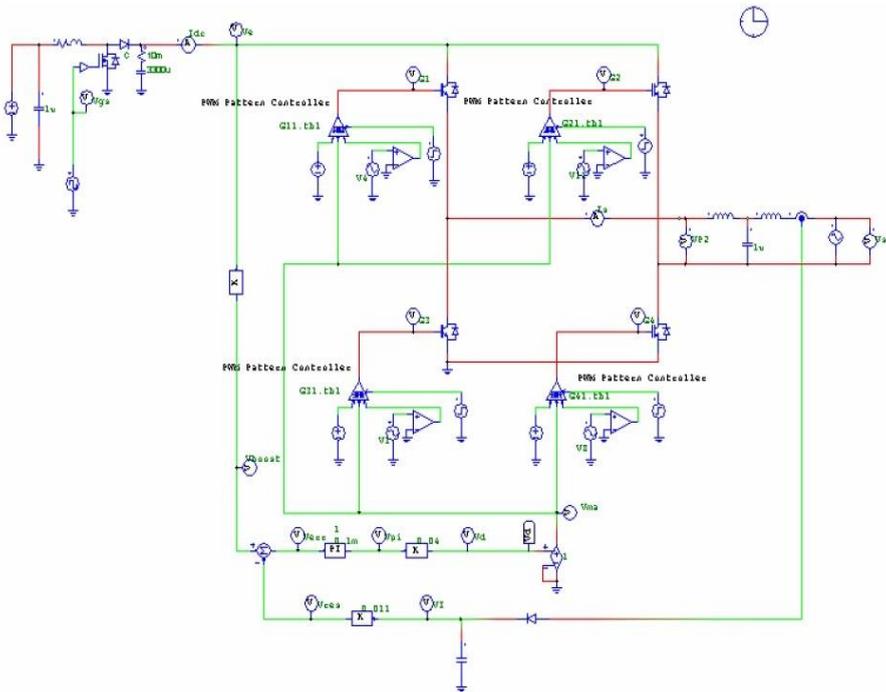


Fig. 11: Simulation circuit of PV system connected to the grid

In figure 12, the inverter output voltage, V_{inv} , the inverter output current, I_{out} the grid Voltage V_{grid} .

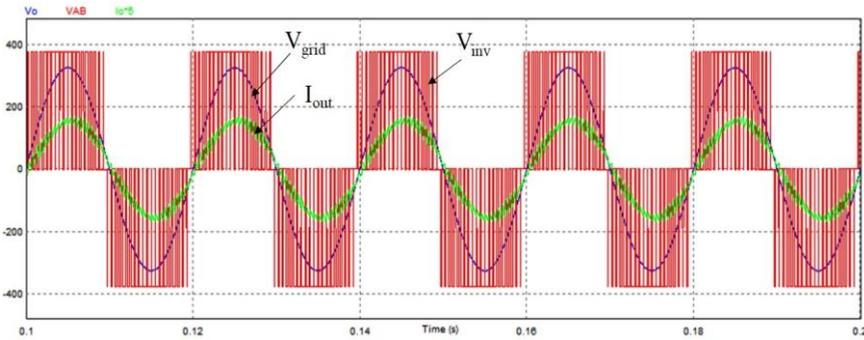


Fig. 12: Simulation circuit of PV system connected to the grid

7. CONCLUSION

In this paper, a design of the photovoltaic inverter connected to the grid has been presented. The proposed control strategy is based on SPWM patterns. This proposed method permit to cover a wide powers range with very few PWM patterns.

As main advantages, the flexibility design, which allows further optimization, and reduced size in comparison to other topologies. The analysis of the behavior of this control strategy for single-phase inverter connected to the grid via an L or LCL filter has been developed

The simulation results validate the theoretical predictions; and show the viability of the PWM method used, the simplicity of the digital implementation, reduction of the memory requirements, and power calculation for the proposed control. This proposed method have been implemented en FPGA.

REFERENCES

- [1] L. Hassaine, E. Olías, J. Quintero and V. Salas, 'Overview of Power Inverter Topologies and Control Structures for Grid connected Photovoltaic Systems', Renewable & Sustainable Energy Reviews, Vol. 30, pp. 796 - 807, 2014.
- [2] L. Hassaine, E. Olías, J. Quintero, and A. Barrado, 'Power Control for Grid Connected Applications based on the Phase Shifting of the Inverter Output Voltage with respect to the Grid Voltage', International Journal of Electrical Power and Energy Systems, Vol. 57, pp. 250 - 260 2014.
- [3] V.G. Agelidis, P.D. Ziogas, and G. Joos, 'Dead-Band PWM Switching Patterns-', IEEE Transaction on Power Electronics, Vol. 11, N°4, 1996.
- [4] A.M. Omar and N.A. Rahim, 'FPGA-based ASIC design of the three-phase synchronous PWM flyback converter', IEE Proceeding Electr. Power Appl, Vol. 150, N°3, 2003.
- [5] S. Mekhilef, N.A. Rahim, 'Xiling FPGA based three phase PWM inverter and its application for utility connected PV system', Proceeding of IEEE Tenco, 02, pp. 2079 - 2082, 2002.

- [6] H.G. Jeong, K.B. Lee, S. Choi, and W. Choi, '*Performance Improvement of LCL-Filter-Based Grid-Connected Inverters Using PQR Power Transformation*', IEEE Transactions on Power Electronics, Vol. 25, N°5, pp. 1320 - 1330, 2010.
- [7] Chenlei Bao, Xinbo Ruan, Xuehua Wang, Weiwei Li, Donghua Pan and KaileiWeng, '*Step-by-Step Controller Design for LCL-Type Grid-Connected Inverter with Capacitor-Current-Feedback Active-Damping*', IEEE Transactions on Power Electronics, Vol. 29, N°3, 2014.
- [8] W. Xuehua, R. Xinbo, L. Shangwei, and Chi K. Tse., '*Full Feedforward of Grid Voltage for Grid-Connected Inverter With LCL Filter to Suppress Current Distortion Due to Grid Voltage Harmonics*', IEEE Transactions on Power Electronics Vol. 25, N°12, pp. 3119 - 3127, 2010.
- [9] A. Reznik, M. Godoy Simões, A. Al-Durra, and S.M. Muyeen, '*LCL Filter Design and Performance Analysis for Grid Interconnected Systems*', IEEE Transactions on Industry Applications, Vol. 99, 2013.
- [10] M. Liserre, F. Blaabjerg, and S. Hansen, '*Design and Control of an LCL-Filter-Based Three-Phase Active Rectifier*', IEEE Transactions on Industry Applications, Vol. 41, N°5, 2005.