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PV Micro-Inverters as Modules of Multilevel Converters

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Abstract: The increasing use of renewable energies, especially Photovoltaic energy generation, has motivated research in the area of power electronics in order to optimize the integration of these sources into the conventional electric system. In general, photovoltaic systems are connected to the AC grid and, for this purpose, use voltage Inverters. Several topologies can be used for this, among them, the Micro-Inverters and the Multi-Modular Converters, both having their advantages and disadvantages. Therefore, the objective of this paper is to integrate the concepts of both technologies in a Modular Multilevel Converter in which each module is given by a Micro-Inverter. The proposed system is modeled in PSIM® and simulation results show that the proposed system presents satisfactory results even under conditions of total or partial shading of PV modules.

Keywords: MMC; MPPT; Multi-Carrier PWM; Renewable energy.

1. INTRODUCTION

Concerns about the generation of electricity from fossil fuels has led to the popularization of using renewable energy sources. In particular, Photovoltaic (PV) solar energy is one of the great options among these sources due to the high solar potential, the modularity of the system and the architectural integration of related equipment (Farret and Simões, 2006).

The comprehension of a photovoltaic system begins in the understanding of the smaller structure of this system, the PV cell. One of the most well-established models of the PV cell is its equivalent electrical circuit, as shown in Figure 1.

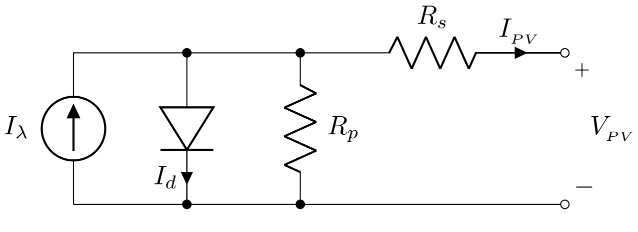

Figure 1. Equivalent circuit of a PV cell.

The current source I_λ is dependent on Irradiance, I_d is dependent on Temperature of the cell. R_p can represent the internal losses across the Shockley diode and R_s models the losses between the cell and its terminals and depends on the manufacturing quality of the PV cells (Farret and Simões, 2006).

The output power of the PV module or a group of modules can be represented by a Power-Voltage (P-V) curve as shown on Figure 2.

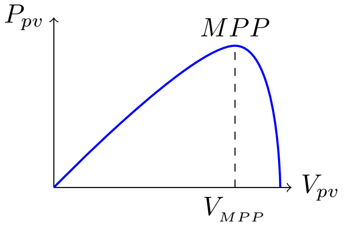

Figure 2. P-V curve of a PV cell.

In many applications it is desired to operate at the Maximum Power Point (MPP) of the P-V curve. This can be performed using one of the various MPP Tracking (MPPT) methods found in literature (Hohm and Ropp, 2003; Ishaque and Salam, 2013), (Rezk and Eltamaly, 2015). In general, the performance of the tracking methods is at the same level with particular advantages and drawbacks. Since this discussion goes beyond the scope of the work, it is sufficient to justify the use of P&O method due to its rapid response and low steady state error (Rezk and Eltamaly, 2015). The MPPT control is made by a DC-DC converter. The use of a Buck-Boost topology (or one of its variations such as Ćuk or SEPIC circuit) is preferred because it is more appropriate to perform MPPT, mainly in situations which the environmental conditions ranges widely (Coelho et al., 2010).

Direct current (DC) applications, such as public lighting poles using LED lamps or fast charging stations for electric vehicles may use the energy directly from the output of the DC-DC converter. In the other hand, alternating current applications (AC) need a voltage Inverter to convert de DC generated energy to one sinusoidal.

PV modules are usually connected in series in order to increase the total voltage of the array. Thus, the PV array is connected to the AC grid through an Inverter, as show in Figure 3. A low-pass filter is used to mitigate the harmonic effects on the main grid. Nevertheless, if the PV module gets shaded due to some construction or structure nearby, the working of solar PV array is compromised (Sher and Addoweesh, 2012). In a series connected string of modules, all the devices carry the same current. The shaded cells may act as loads, decreasing the power delivered from the array and even damaging irreversibly the modules (Ramabadran and Mathur, 2009). One of the long-term effects of high output voltage of the PV strings is the Potential Induced Degradation (PID). The extent of the voltage bias degradation is linked to the leakage current from module to ground, through the module frame (Hacke et al., 2011; Pingel et al., 2010). In literature, the module degradation due to PID effect can be grater than 20% (Hacke et al., 2011), total power losses can be around 32% (Pingel et al., 2010), and the open circuit voltage be reduced by 40% (Luo et al., 2017).

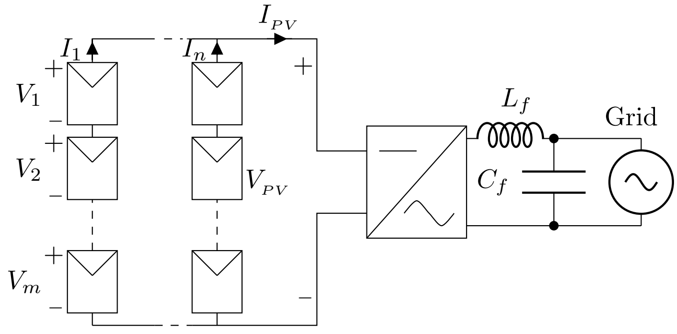

Figure 3. General schematic of a conventional PV Inverter

In this scenario, the Micro-Inverters (MI) come as an alternative to conventional Inverters topologies. In the Micro-Inverter system, every PV module has its own Inverter and the output of each can be directly connected to the grid (Phan-Tan, 2018). Several topologies of MI have been documented in literature (Sher and Addoweesh, 2012; Phan-Tan, 2018). Basically, an Micro-Inverter is composed of a DC-DC converter which tracks the MPP, an Inverter itself, and an AC filter. A low frequency transformer must be used, in case of using a non-isolated DC-DC converter topology. The general topology of a grid connected PV system using a MI is presented in Figure 4.

Micro-Inverters have higher lifespan than conventional Inverters because there is no need of bulky input capacitors. Also, they are low-cost due to decrease in balance of system, easy to instal, and systems using MI are more reliable (Sher and Addoweesh, 2012). However, if an MI system develops a fault as a result of environmental or technical issues, it can be very difficult to repair it since decentralization leads to a much larger number of electronic components in the system as a whole (Sher and Addoweesh, 2012). The need for a transformer is another issue. The low frequency transformer is bulky and is another source of power losses. In case of using a isolated DC-DC converter, the design itself is another concern, due to the higher skin effect, eddy currents and hysteresis losses of high frequency operation (Mohan and Undeland, 2007).

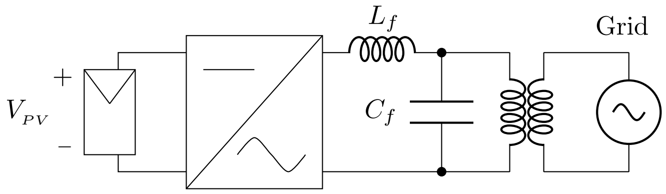

Figure 4. General schematic of a Micro-Inverter based PV system

Another way of connecting PV to AC systems is using the Modular Multilevel Converter (MMC) concept. In general, the main purpose of a Multilevel Converter is to divide the total voltage or current of one single converter among several smaller converters (modules) or to obtain an alternating n-step waveform with low Total Harmonic Distortion (THD) (Braga, 2000). It is possible to reduce the switching losses by reducing the operational frequency of the converter obtaining the same harmonic performance as two-level Inverter (Carrasco et al., 2006). Multi-Carrier Sinusoidal PWM (SPWM) strategies are widely used because their implementation in low voltage modules is comparatively easy. The proposed topology uses Phase Disposition PWM technique which presents better results than other similar SPWM techniques, producing less harmonic distortion for the output voltage (Harin et al., 2017; Darus et al., 2014; Rajan and Seyezhai, 2013). Furthermore, increasing the number of modules results in a higher output voltage and the use of a transformer is not required for high voltage AC applications. The main disadvantage of using MMC in PV systems is the same of using conventional high voltage Inverters: the need of a high number of modules in each PV string.

Taking into the account the above, the work is to present a topology of a modular multilevel converter in which each module comprises a Micro-Inverter. In this way, the main contribution the work is to minimize problems associated with the series connection of a large number of photovoltaic modules and to combine the advantages related to modular converters such as lower harmonic content and the achievability of obtaining high output voltage level, avoiding the need of using transformers in the output of Micro-Inverters if they were operated individually.

2. METHODOLOGY

A 3-level cascaded H-bridge MMC in which each PV panel and its corresponding DC-DC converter act as a separated voltage source is proposed and modeled in PSIM®. Each set is formed by a PV panel, a DC-DC converter and a full-bridge Inverter forms a Micro-Inverter which, in turn, can be interpreted as a MMC module. The complete circuit diagram of the modeled system is shown in Figure 5.

On the proposed system, two 120 Wp PV panels, represented by the built-in PSIM® model of solar module, is

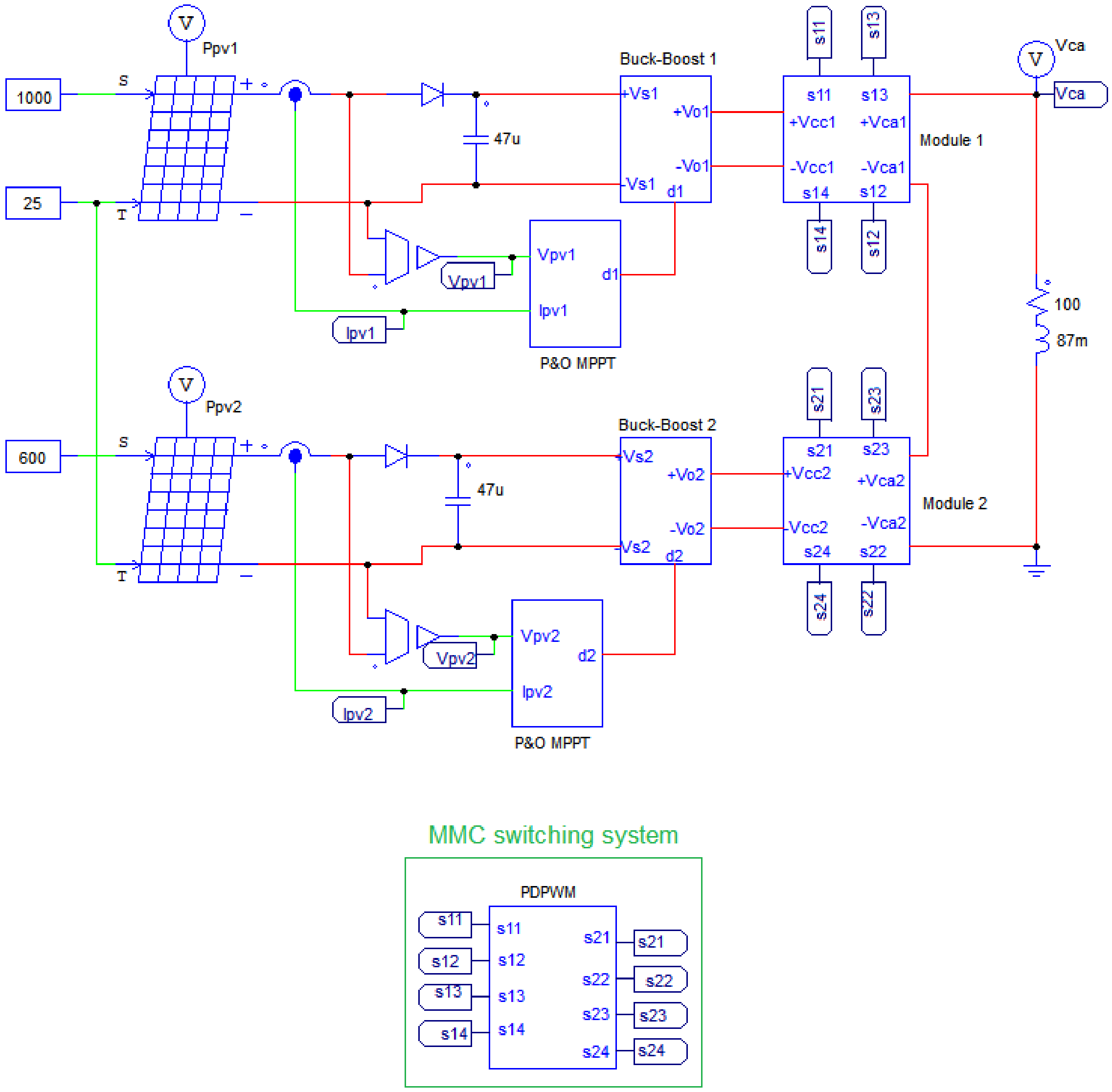

Figure 5. Circuit diagram of the PSIM® system model.

used. Each panel is connected to a MMC module through a buck-boost DC-DC converter using Perturb-and-Observe MPPT algorithm. The DC-DC circuit model is shown in Figure 6. The inductor and capacitor values was chosen in order to keep the converter in Continuous Conduction Mode (CCM) and to provide better current and voltage ripple. The block diagram of the P&O method modeled in PSIM® is described in Figure 7.

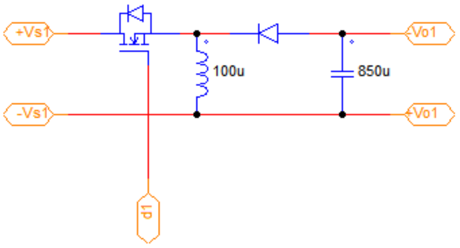

Figure 6. Equivalent circuit of the buck-boost converter.

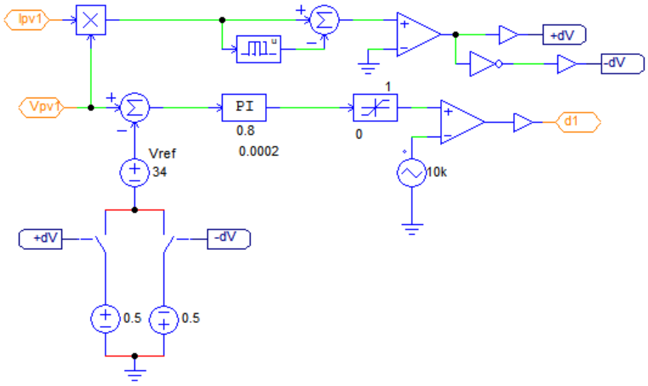

Figure 7. Block diagram of the P&O method.

As previously described, H-bridge inverter is used to convert the output DC voltage from the Buck-boost converter and its model is shown in Figure 8. Finally, the modeled switching control system is represented in Figure 9.

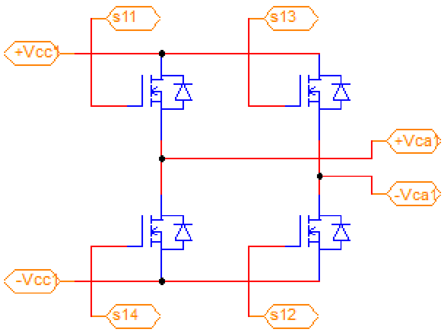

Figure 8. Circuit model of the H-bridge inverter.

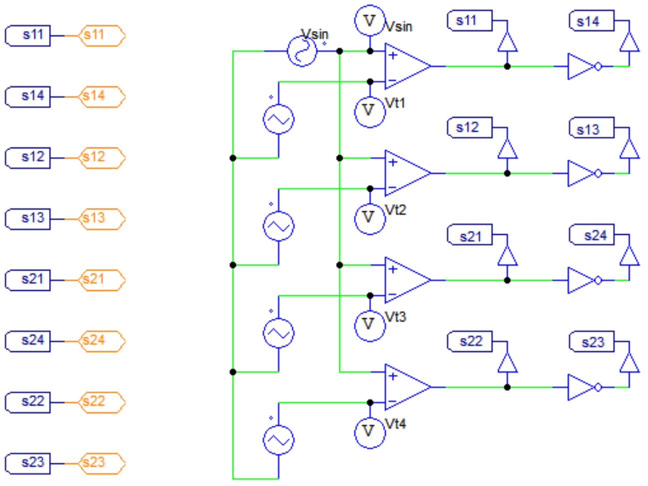

Figure 9. Schematic of MMC Multi-Carrier PWM Switching circuit.

In the simulations, the amplitude modulation index is $m_a = 1$ and frequency modulation index is $m_f = 33$. The grid reference frequency os $f = 60\ Hz$.

3. SIMULATION RESULTS

3.1 Partial Shading

The analysis of partial shading is crucial for assigning the PD-PWM carriers to the switches of each MMC module. As shown in Figure 5, the upper PV module has irradiance of 1000 W/m^2, while the lower one has 600 W/m^2.

When the carriers are assigned as shown in the lower graphic of the Figure 10, it is noted that the output voltage is asymmetrical, i.e., the average voltage is not equal to zero. Such an imbalance is evident, since the two upper waves are designated for first module which is generating more power while the other two triangular waves are assigned to controlling the second module.

Thus, an alternative is to designate the upper and lower carriers for the first module, while the intermediates are designated for the control of the second one. This results in a symmetrical alternating wave, as shown in Figure 11

It is necessary to consider that, in this case, the switches of one of the modules will be overloaded, since there will be a circulating current for a longer time, which may cause greater thermal losses. However, it is possible to adopt

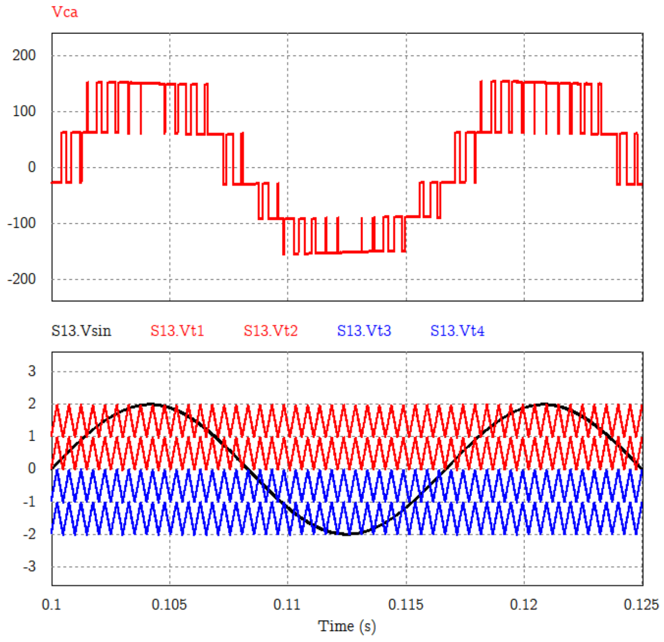

Figure 10. Asymmetrical voltage under partial shading (top) and PD-PWM technique (bottom).

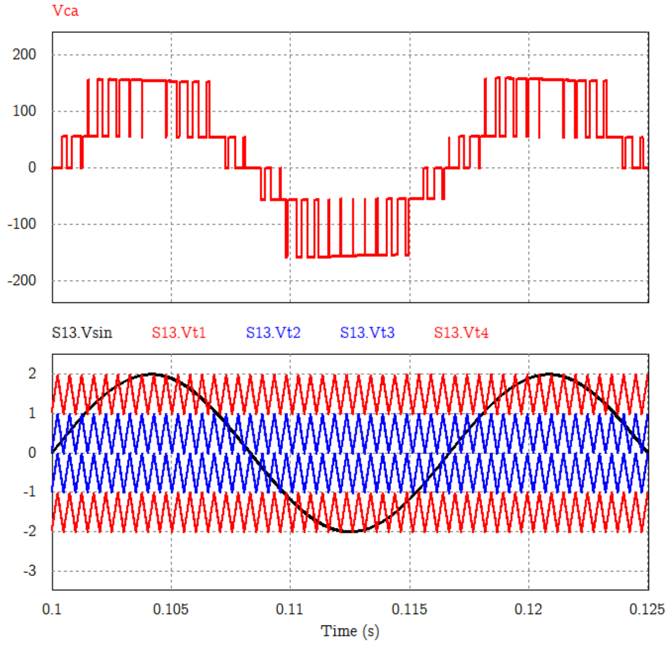

Figure 11. Symmetrical voltage under partial shading (top) and PD-PWM technique with different carriers designation (bottom).

some control strategy that performs the periodic exchange of the carriers designated for each module.

3.2 Irradiance Variation

It is important to evaluate the behavior of the system under irradiance disturbance. A cloud or another moving object near the PV system can eventually produces this phenomenon. The effectiveness of the MPPT method can be analyzed, as well as the general behavior of the generated AC voltage. For this analysis, it is applied a reduction of 250 W/m^2 on the irradiance on both PV modules. The simulation results can be observed in Figure 12.

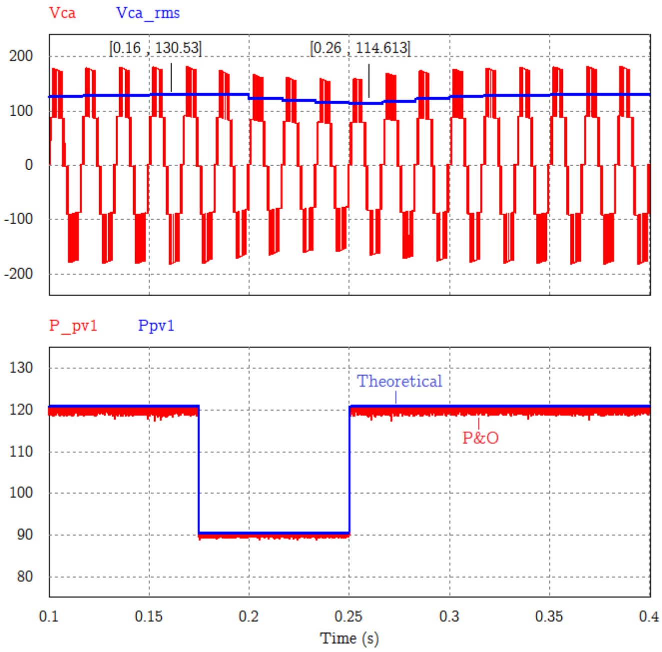

Figure 12. Output voltage of the MMC (top) and PV power (bottom).

The MPPT method is able to track the maximum power point before, during and after the disturbance, which is easy to see on the output voltage graphic of the first PV panel. The curves for the second panel was neglected, since the behavior is the same. In addition, naturally, the Root Mean Square (RMS) value of AC voltage is reduced. However, it is observed that the waveform remains symmetric, with no change in the phase, and with recovery time of approximately four cycles after the end of the shading.

3.3 Filtering and Load Behavior

3.3.1 Purely Resistive Load The previous simulations were performed using a single resistance of 100 Ω which models a load that represents only the consumption of active power. However, it is interesting to analyze the behaviour of the system from the point of view of harmonic distortion. Additionally, a LCL filter is considered in order to evaluate a practical grid connected PV system, in which is mandatory low levels of THD. Using the FFT tool of the PSIM® it is possible to obtain the spectral diagram of the synthesized voltages and currents with and without using a LCL filter, as seen on Figure 13. In this case, $L_1 = L_2 = 1\ mH$ and $C = 100\ \mu F$.

3.3.2 Inductive Load The same procedure was carried out when considering an inductive load with power factor of 0.95. It means an inductance of 87 mH by keeping the resistance equal to 100 Ω. Using the same LCL filter, the spectral diagram of the generated voltages and currents on the MMC, without and with AC filtering, is shown in Figure 14. It is interesting to observe that a small quantity of reactive power, represented by the inductance, reduces the need for AC filtering in some specific applications.

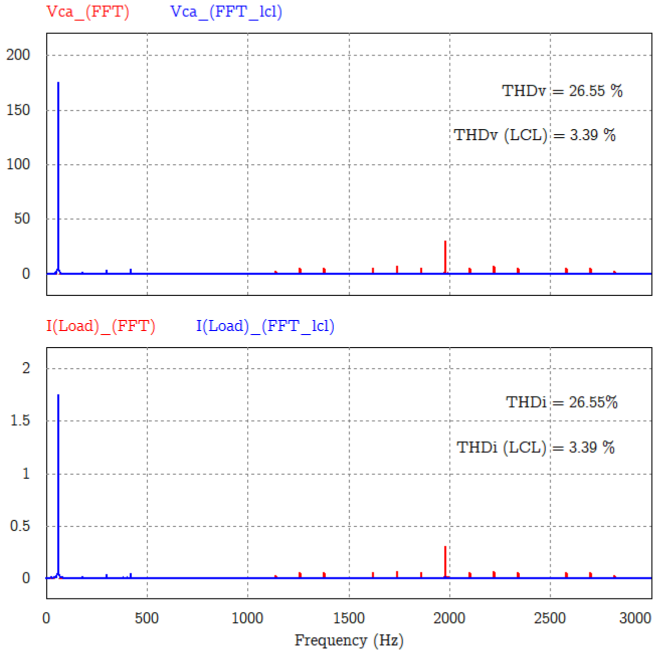

Figure 13. Spectral diagram of the synthesized voltages (top) and currents (bottom) for resistive load with (blue) and without (red) AC filtering.

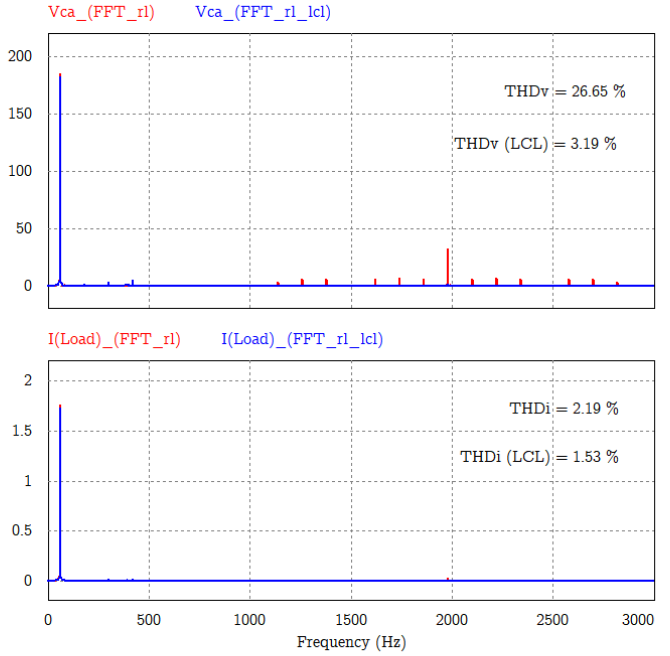

Figure 14. Spectral diagram of the synthesized voltages (top) and currents (bottom) for inductive load with (blue) and without (red) AC filtering.

4. CONCLUSIONS

This work proposed a three-level cascaded full-bridge MMC topology in which each module consists of a Micro-Inverter using a buck-boost converter and a regular full-bridge Inverter. Perturb-and-Observe MPPT method was used to extract the maximum power from the PV modules in order to keep output voltage amplitude of the MMC as constant as possible.

The system was modeled in PSIM® and simulations revealed that the system had a good behavior even in cases of partial shading or irradiance variation, in which the RMS value reduced 12.5% for a 25% of irradiance reduction. Symmetrical voltage under partial shading is obtained when using PD-PWM technique with different carriers designation. Harmonic distortion analysis was also performed and has shown a $THD_v = 26.6\ \%$ without filtering and $THD_v = 3.4\ \%$ with a LCL filtering.

The present work opens possibilities for analyzing systems with higher number of modules, and other MMC topologies, as well as three-phase Inverters and alternative switching techniques. For future works, it is intended to compare the behavior of conventional PV-inverters and the proposed one when connected to the AC grid.

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