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# Generalized Discontinuous PWM strategy applied to a grid-connected Modular Multilevel Converter

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***Abstract*— This paper presents a new PWM strategy for the control of active and reactive power flow, applied to a three-phase power inverter connected to a microgrid. Power quality and reactive compensation are essential in the integration of renewable energy sources in small grids (stand-alone mode or connected to the utility grid). The control algorithm of the grid-connected system is applied for voltage control. This technique provides independent control of the active and reactive power flow in the utility grid while maintaining constant the DC-link voltage. As a novelty, a Generalized Discontinuous PWM technique is implemented in the control algorithm of the grid-connected converter. Losses in the converter are reduced while the efficiency of the equipment is increased. As a technological innovation, in addition to the power flow control technique, a modular multilevel converter (MMC) is introduced. The main purpose of the system is to improve voltage unbalance and harmonic compensation in stand-alone grids. Some advantages of the model developed here include the cellular concept, easy thermal design, increased system efficiency and improvement in the system expansion capacity. The simulation model has been developed and tested using MATLAB/Simulink software.**

***Keywords*— *Reactive Power Compensation, Active Power Injection, Generalized Discontinuous PWM technique, Modular Multilevel Converter (MMC), Stand-alone Microgrid, FACTs.***

## I. INTRODUCTION

In this last decade, renewable energies are playing a prominent role in power generation. As is known, renewable energy systems are highly dependent on environmental variables, such as sun and wind, which have stochastic behaviour. Among renewable resources, photovoltaic (PV) energy is more popular because it is clean and environment-friendly. Unbalanced and non-linear load conditions are the most common case in low-voltage microgrids, where most of the loads are usually single-phased. In addition, the continuous development of non-linear loads such as converters, fluorescent lamp, AC and DC-drives, switched-mode and uninterruptable power supplies are causing harmonic pollution problems in the power distribution system. Thus different passive filter configurations are connected to the circuit, to solve these harmonic-related problems, since it is a low-cost solution. Thus, for example, static VAR compensator (SVC) topologies have been proposed to solve the problems caused by harmonics. Therefore, it is necessary to design a control strategy in distributed generation units (DG) to improve the performance of microgrids under unbalanced and non-linear load conditions, [1].

At present, the quality of energy is essential for the correct integration of renewable energies in the different microgrids. So, Gandoman et al. [2] develop a thorough review of FACT technologies, with the purpose of improving the quality of energy in smartgrids. Similarly, Sampaio et al. [3] and Artal-Sevil et al. [4] propose a strategy to control the active and reactive power flow between a DG and utility grid through a three-phase grid-tie inverter. This improves the efficiency of the converter. The proposed strategies mitigate possible disturbances and nonlinearities in the system. Other authors, such as Moreno & Mojica-Nava [5], propose a robust control scheme to improve the integration of renewables energies, into a DC distribution grid. DC microgrid is a concept of a highly efficient distribution scheme that has several advantages over AC to effectively integrate renewable energy resources into an interconnected grid. Finally, Mohd et al. [6] present a different control strategy for harmonic current compensation.

The paper presented here incorporates the effective use of a photovoltaic system destined to perform active power injection and also the reactive power compensation in a small microgrid. As a result, a modular multilevel converter is presented, as well as the power flow control technique used. The purpose has been to improve harmonic compensation and voltage unbalance in stand-alone grids. Thus a DPWM technique is implemented. This strategy allows a power flow control in the grid-connected converter. Using the generalized discontinuous PWM method causes a decrease in the losses of the power devices, thus improving the overall efficiency of the system. This document is organized as follows. Section I shows a brief introduction to the presented problem and the state-of-the-art. Section II presents a Modular Multilevel Converter (MMC) and its simplified equivalent model. Section III shows the Generalized Discontinuous PWM control technique implemented (GDPWM). Section IV describes the control strategies. The control system for active power injection and reactive power compensation is also described. Section V shows the different results obtained from the simulation. The Matlab/Simulink software has been used. Finally, the conclusions and some brief considerations are described in Section VI.

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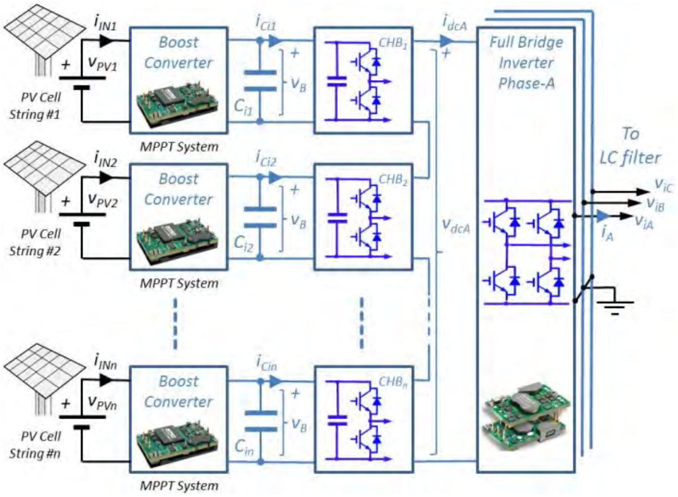

Fig. 1. Modular Multilevel Converter (MMC) block diagram. The system operates as three generators in a wye configuration ($v_{iA}$, $v_{iB}$, $v_{iC}$ voltages).

## II. MODULAR MULTILEVEL CONVERTER

Modular multilevel converters (MMC) are also known as scalable technology since the voltage level is verified by the number of submodules. Thus, MMC is a reasonably young technology with a promising short-term future in medium voltage DC systems. Some examples of MMC topology implementation are large-scale PV generation, the integration of large wind turbines in DC grids or the interconnection of wave farms [2]. A cascaded multilevel inverter is a suitable architecture for PV systems due to some of its advantages, such as independent maximum power point tracking (MPPT) for segmented PV assemblies, transformerless topology, the possible application of low voltage devices, etc. However, all these advanced features and performance can only be achieved with an appropriate control algorithm. On the other hand, the basic concept of the MMC is the cascade connection of several cells with individual control systems. This paper proposes a technique for controlling the power flow (P, Q), applied to a three-phase power inverter connected to a microgrid.

### *A. Converter Architecture*

Figure 2 shows the PV system implemented. The model presented includes *n* multilevel inverter modules in cascade for each phase, where each basic-cell ($CHB_j$) is in turn connected to a Boost converter. On the other hand, with the help of an MPPT algorithm (Maximum Power Point Tracking), it is possible to obtain the maximum energy of the PV panels. Boost converter control algorithm uses the parameters $v_{PVj}$ and $i_{INj}$ (voltage and current in the PV panels) to obtain the reference voltage, see Fig. 1. By means of the external voltage loop and internal current loop, it is possible to achieve the controlled duty cycle of the Boost converter.

The architecture proposed here requires creating different PV strings. In this way, each Boost converter is connected with individual PV strings, to ensure the voltage $v_B$ (voltage regulator mode). On the other hand, cell balance techniques are also easier to achieve; usually, in this architecture, each converter can reach the MPPT in each PV panel. In each basic-converter cell, $C_{ij}$ is the value of the energy storage capacitor, which provides a stable DC voltage for the $CHB_j$ cell while ensuring the normal operation of the MMC. According to the definitions of current and voltage are shown in Fig. 2, the expressions for $v_{dc}$, $i_{dc}$ can be written as follows:

$$v_{dc} = \sum_{j=1}^{n} v_{Oj} = \sum_{j=1}^{n} s_j v_{Bj} \tag{1}$$

$$i_{Cij} = s_j i_{dc} \tag{2}$$

where $v_{dc}$ is the theoretical value of the voltage applied on Full-Bridge in each phase; $v_{Oj}$ is the voltage value of the basic-cell in the *jth* module; $v_{Bj}$ is the voltage value in the output of the Boost converter in the *jth* module; $s_j$ is the switching status of the *jth* basic-cell, this parameter adopts the values $s_j = (1, 0)$ that correspond to the connected or disconnected module, respectively. While $i_{dc}$ is the current provided by the MMC system in each phase and $i_{Cij}$ is the current in the *jth* basic-cell.

TABLE I. VOLTAGE LEVEL & SWITCHING STATE IN THE BASIC CELL.

| **Switching State** | | **Voltage** | **Status** |
|---|---|---|---|
| $M_{1H}$ | $M_{1L}$ | $v_{Oj}$ | $s_j$ |
| 0 (off) | 1 (on) | 0V | 0 |
| 1 (on) | 0 (off) | $v_{Bj}$ | 1 |

In the mentioned topology, the $v_{Bj}$ voltage remains constant at +50V. The voltage ripple in the $C_{ij}$ capacitor is considered negligible because the switching frequency ($f_{sw}$) of the Boost converters is 100kHz. In the proposed case, the MMC system consists of 4 basic-cells, then j = 4. Table I presents the parameters ($v_{Oj}$, $s_j$) and switching states in a basic-cell. Thus the supply voltage $v_{dc}$ to the Full-Bridge converter is constituted by the connection of several half-bridge cells in series. As seen in Fig. 1, each basic-cell has an external voltage $v_{Bj}$ controlled by two switches. These two switches ($M_{1H}$ and $M_{1L}$) operate in an alternative mode, see details in Table I. The cell voltage is by-passed with $M_{1L}$ "on" and $M_{1H}$ "off", or added to the DC bus voltage by $M_{1L}$ "off" and $M_{1H}$ "on", eq. (1). In other words, the $CHB_j$ half-bridge module can only generate a positive voltage. To achieve both voltage outputs (positive and negative) a Full-Bridge topology is necessary.

### *B. Simplified model*

The three-phase modular multilevel converter (MMC) implemented is shown in Fig. 1; with j = 4 a 9-level converter in each phase can be developed. The main advantage is that this topology is scalable to obtain more voltage levels. This structure allows switching the basic-cells to the fundamental frequency, and thus reduces the switching losses in the converter and improves its efficiency. Therefore, it presents a solution to supply AC, without a transformer, particularly when the DC source can be divided into several isolated parts, such as PV panels.

In the same way, Fig. 2 shows the equivalent circuit of the grid-connected MMC converter. Where $v_{PV}$ and $i_{IN}$ correspond to the DC-link voltage and current respectively; $i_A$, $i_B$, $i_C$ represent the currents in the different lines of the utility-grid; $v_{iA}$, $v_{iB}$, $v_{iC}$ represent the output voltages of the converter; $L_g$, $R_g$

are the grid filter inductance and parasitic resistance respectively and $v_{gA}$, $v_{gB}$, $v_{gC}$ are the ideal three-phase grid voltages. State-space equation of the grid-connected inverter in three-phase steady-state coordinates is presented in eq. (3).

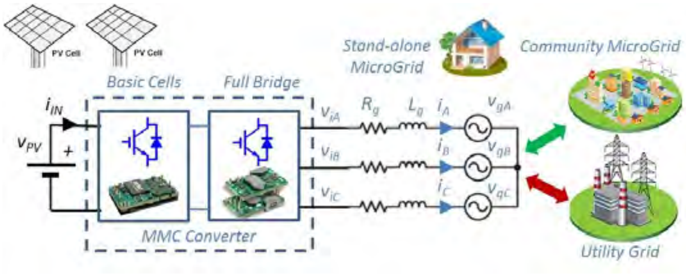

Fig. 2. Equivalent diagram of the grid-connected MMC converter. The whole system can be simplified as three generators in wye configuration ($v_{gA}$, $v_{gB}$, $v_{gC}$ voltages).

$$\begin{bmatrix} v_{iA} \\ v_{iB} \\ v_{iC} \end{bmatrix} = L_g \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + R_g \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} v_{gA} \\ v_{gB} \\ v_{gC} \end{bmatrix} \tag{3}$$

where $v_{ij}$, $v_{gj}$ (j = A, B, C) represent the three-phase voltage on the inverter side and the utility grid side respectively; and $i_j$ (j = A, B, C) represent the three-phase current. At the same time, Fig. 3 presents the simplified circuit for the single-phase grid-connected MMC converter. The phase voltage in the multilevel inverter is the result of the interconnection (on↔off) of the different basic cells $CHB_j$. Using MMC topology decreases the requirements of the grid-filter ($L_g$, $R_g$). At the same time, the $i_A$, $i_B$, $i_C$ currents are sinusoidal as a result of the applied filter [7].

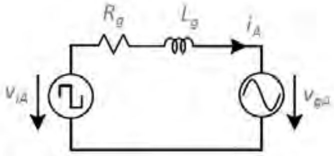

Fig. 3. Simplified circuit for the single-phase grid-connected MMC converter in PV system.

## III. GENERALIZED DISCONTINUOUS MODULATION

The modulation technique selected for the control algorithm also has an important role in the functionality of the converter [8]. The purpose is the transfer of active power from the PV system to the utility grid, as well as the unbalances compensation and the suppression of harmonic currents; or the reactive power compensation. It is also important to indicate that the linearized model used in the controller design is obtained by linearization of feedback. Its purpose is to reduce the nonlinearities of the system, improve controller performance and suppress possible disturbances [9]. There are several methods to control the behaviour of the fundamental voltage generated by a three-phase inverter in the load or injected into grid [10].

### *A. Discontinuous PWM Modulation*

In general, the adoption of the PWM strategy or modulation algorithm is intended to improve the behavior of the system: improve harmonic content (THD) or dynamic response, reduce switching losses, increase conversion efficiency, etc. One of the most important techniques is the discontinuous PWM modulation (DPWM). There are several types of algorithms that have in common the injection of a zero-sequence signal (ZSS). In three-phase inverters, these signals can be added additionally on the modulation in order to improve the performance. This PWM technique allows us to increase the linear range of the modulation index (MI) in the converter.

Furthermore, the built-in harmonics are canceled in the line voltages. As there is a rejection of some harmonics the switching events can be reduced, also improving the switching losses in inverter power devices. This is usually possible because these systems only perform switching in 2/3 of the signal cycle. The main difference in the PWM modulation techniques analyzed is the algorithm used to obtain the ZSS signal. This mathematical function is incorporated within the "conditions block", see Fig. 4. Next, to achieve discontinuity in the reference signals, a zero-sequence signal $v_{ZSS}$ is injected. Thus, the generalized discontinuous reference signals $v_{jZ}$ (j = A, B, C) per phase are expressed as:

$$v_{jZ} = v_j + v_{ZSS} \tag{4}$$

where $v_{ZSS}$ represents the zero-sequence signal and $v_j$ (j = A, B, C) correspond to the reference sine signals. The control signals of the different power Mosfets have been obtained as a result of the intersections between the triangular carrier signals and the reference signals $v_{jZ}$.

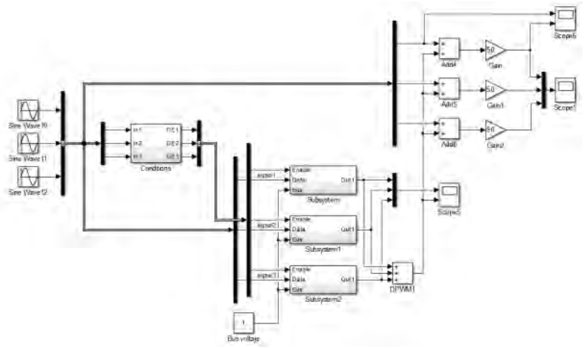

Fig. 4. Block diagram of the Generalized Discontinuous PWM modulator (GDPWM) developed using the Matlab/Simulink software.

The schematic diagram of the GDPWM modulator used and implemented in Matlab/Simulink, is shown in Fig. 4. The generated zero-sequence signal is characterized by being periodic; it is also discontinuous and has three times the fundamental frequency. This $v_{ZSS}$ signal is obtained through the "add" block that interconnects the output of the different subsystems, see Fig. 4. The sinusoidal reference wave with the injection of the zero-sequence signal versus the DPWM signal obtained, can be observed in the different waveforms shown in Fig. 5. In all cases a carrier-based PWM modulator (CB-PWM) has been used.

The literature includes different types of discontinuous PWM algorithms, among which are: DPWM0, DPWM1, DPWM2, DPWM3, etc., see Fig. 5. Considering the different DPWM modulation strategies mentioned, the methods that are symmetric and, therefore, produce the same power losses in the upper and lower electronic power devices of the converter are the most implemented. It should also be noted that although the phase voltages are not sinusoidal, their composition in the secondary winding in the transformer (delta connection) is a sine wave. For variable power factor (PF), the modulation method is selected by tracking the minimum attainable switching loss of the popular DPWM techniques available, see diagram in Fig 6. In this case, the power factor is given by the reactive power compensation required from the system. A GDPWM technique is proposed to coordinate active and reactive power flows, whose objective is to improve the power quality and reliability in the system.

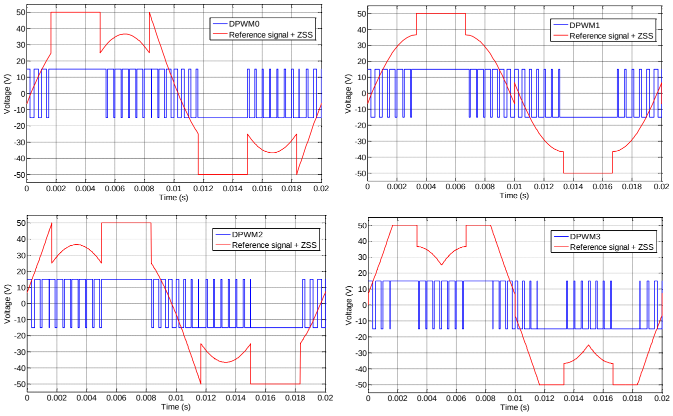

Fig. 5. Discontinuous modulation waveforms (DPWM0, DPWM1, DPWM2 & DPWM3 techniques) vs. reference wave with zero sequence signal injection (ZSS).

### *B. Switching Losses*

Each of the aforementioned strategies is optimal, in terms of switching losses ($P_{sw}$), in an interval of $\varphi$ (Power Factor). Some authors have proposed different combinations of these discontinuous techniques in order to minimize inverter losses [11]. A coefficient called switching loss factor (SLF) is defined, see eq. (5). SLF is calculated as a function of the current phase angle $\varphi$. The calculations assume operating conditions in steady-state, where the currents are sinusoidal. Figure 6 shows the SLF (%) for an output current of fundamental frequency, at different phase angle $\varphi$. Thus, the diagram presents the SLF characteristics of the different DPWM techniques, along with the optimum SLF solution of the GDPWM method. Adaptive control keeps the losses at the minimum.

$$SLF = \frac{P_{sw}\big|_{DPWM}}{P_{sw}\big|_{SPWM}} \tag{5}$$

With DPWM techniques, switching losses are significantly influenced by the modulation method and the power factor angle. Therefore, the load power factor and the modulation technique together determine the time interval in which the load current ($i_A$, $i_B$, $i_C$) is not commutated, see Fig. 5. Thus, depending on the angle $\varphi$ different modulations are applied: DPWM3 for $+90^o \geq \varphi \geq +75^o$; DPWM2 for $+75^o \geq \varphi \geq +15^o$; DPWM1 for $+15^o \geq \varphi \geq -15^o$; DPWM0 for $-15^o \geq \varphi \geq -75^o$; DPWM3 for $-75^o \geq \varphi \geq -90^o$; see Fig. 6.

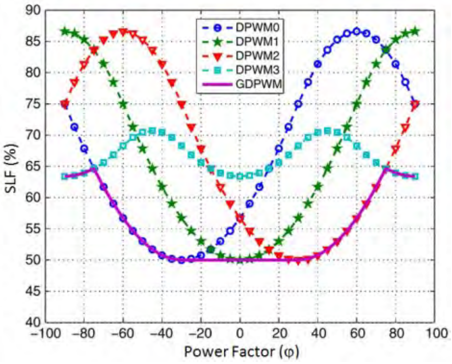

Fig. 6. Switching loss factor (SLF) based on power factor ($\varphi$). Reduction of switching losses for Generalized Discontinuous PWM.

## IV. CONTROL STRATEGY

The control strategy uses the Park ($K_P$) and Clarke ($K_C$) mathematical transformations. The purpose is to convert the vector into the *abc* reference frame to the *dq* reference frame. The reference frame transformation works with the conversion of current components from the three-phase stationary system (*abc*) to the rotating coordinate system (*dq*). This algorithm allows us that the three-phase load currents in the *abc* system are converted into currents in the *dq* frame using equations. (6), (7). The main purpose of the Park transform ($K_P$) is to rotate the reference frame of a vector at an arbitrary frequency.

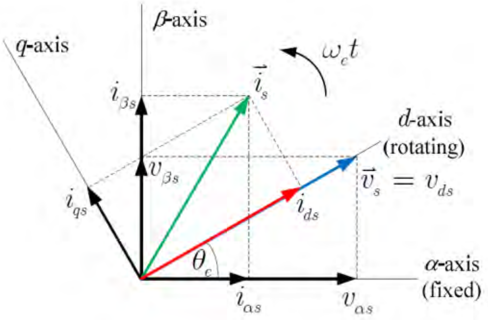

Fig. 7. Phasor diagram in the grid-connected converter. Application example in the Clarke and Park Transformation.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{7}$$

The technique proposed in the power control loop uses the well-known expressions for the transfer of active and reactive power, see eq. (8). Thus, the instantaneous active and reactive power ($P$, $Q$) exchanged in the reference frame *dq* is,

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{8}$$

where $P$ and $Q$ are desired active and reactive power in the converter; while $v_d$ and $v_q$ are voltages at the PCC in the d-axis and q-axis respectively.

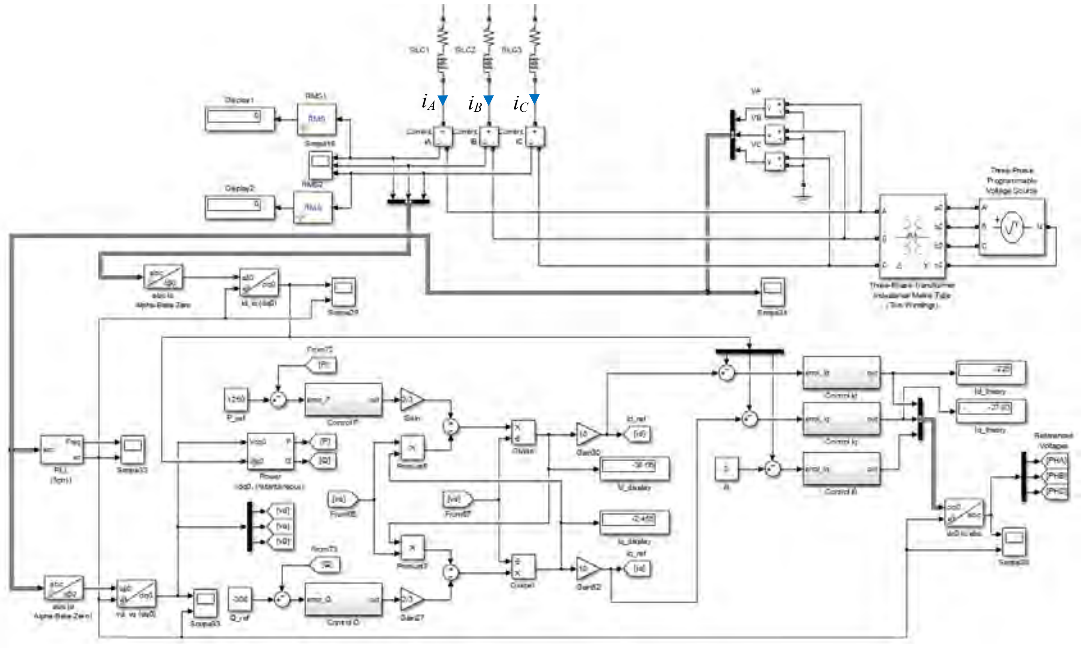

Fig. 8 Block diagram in Matlab/Simulink of the proposed control algorithm.

Block diagram of the model developed in Matlab/Simulink is shown in Fig. 8. From the reference power parameters $P_{ref}$ and $Q_{ref}$ (incorporated by the users), together with the values of active power injection ($P_{real}$) and reactive power compensation ($Q_{real}$) introduced in the utility grid, errors are estimated; see the control diagram. In this case, the power grid has been simulated as a three-phase voltage source. PI-controllers associated with each current component ($i_d$, $i_q$) can also be observed. The results obtained by the linearized model have shown the robustness of the system. Thus the effect of current and voltage feedback loops on the stability has been analyzed. A phase-locked loop PLL is the control module that provides the frequency and phase parameters in the three-phase system.

The *abc* components of the control signals in the converter, are generated from the current errors. The PI-controller is used in the inner loop as a current compensation technique ($i_d$, $i_q$). Using the inverse Park transformation ($K_{CP}^{-1}$), the *dq* axis is converted back to the *abc* coordinate system. The reference current signals in *dq* rotating frame are converted back to *abc* stationary frame using the following equations (9),

$$\begin{aligned} i_a &= i_d \sin(\omega t) + i_q \cos(\omega t) \\ i_b &= i_d \sin(\omega t - 120^\circ) + i_q \cos(\omega t - 120^\circ) \\ i_c &= i_d \sin(\omega t + 120^\circ) + i_q \cos(\omega t + 120^\circ) \end{aligned} \tag{9}$$

In this way, zero-sequence currents are suppressed for the balanced three-phase system. Two PI-controllers (power and current values) improve the response time and the quality of the output current (dynamic response analysis). Therefore, it is possible not only to inject active energy from renewable sources but also to improve reactive energy compensation. The proposed new control strategy operates satisfactorily both in a stable state and in a dynamic state and allows us to control the active power injection and reactive power compensation in real-time.

TABLE II. SYSTEM PARAMETERS WITH THEIR VALUES.

| System parameters | Value |
|---|---|
| L Filter | $L_f = 5$mH |
| R Filter | $R_f = 1{,}5\Omega$ |
| DC link voltage | $V_{DC} = +200$V |
| Grid voltage (line to line) | $V_{Grid} = 380V_{rms}$ |
| Grid frequency | f = 50Hz |
| Distribution transformer ratio | rt = $2/\sqrt{3}$ |
| Transformer configuration | Delta-grounded Wye |
| Internal Resistance $R_{on}$ | $R_{on} = 0{,}02\Omega$ |
| Internal diode resistance $R_d$ | $R_d = 0{,}12\Omega$ |
| Snubber $R_s$; $C_s$ | $R_s = 10k\Omega$; $C_s = 10nF$ |

TABLE III. CONTROLLER PARAMETERS.

| System parameters | Value |
|---|---|
| Current loop parameters $i_d$; $i_q$ | kp = 1,125; ki = 1,75 |
| Voltage loop parameters P | kp = 22,5; ki = 25 |
| Voltage loop parameters Q | kp = 12,5; ki = 15 |

The system parameters used are shown in Table II, while the PI controller parameters are presented in Table III. The current waveforms ($i_A$, $i_B$, $i_C$) during the active power injection and reactive power compensation (P = +1,25kW; Q = -0,25kVAr, capacitive power factor) in the three-phase microgrid are shown in Fig. 9. A balanced system has been considered. It is observed that the quality of the current wave is good, being negligible the ripple that incorporates. The control algorithm involves a small compensation of reactive power due to the filter and the transformer associated with the grid connection point (PCC). Sometimes it is also possible to connect the system in parallel with the load, in the PCC (Point Common Coupling), to cancel the distortion in the current or compensate for its different harmonics. The steady-state current components ($i_d$, $i_q$, $i_0$) in the *dq* coordinate reference frame, for this assumption, are presented in Fig. 10.

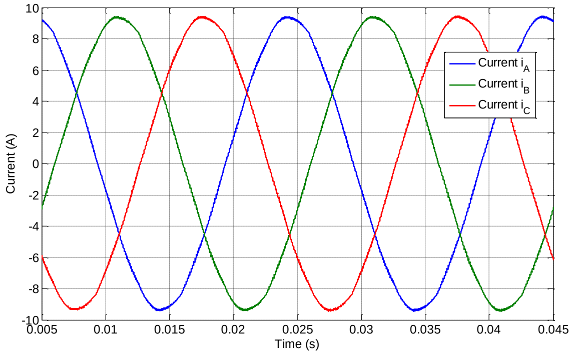

Fig. 9. Current waveforms ($i_A$, $i_B$, $i_C$) during the active power injection (P = +1,25kW; Q = -0,25kVAr) in the three-phase microgrid.

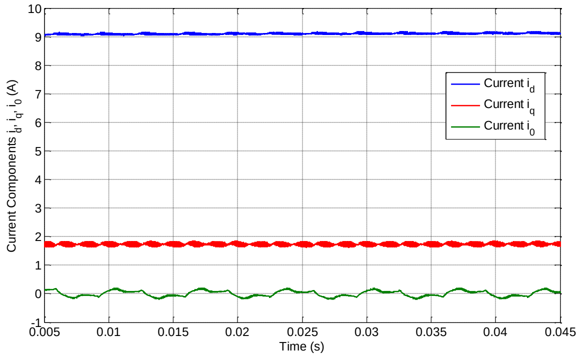

Fig. 10. Current components ($i_d$, $i_q$, $i_0$) in steady-state during the active power injection (P = +1,25kW; Q = -0,25kVAr) in the microgrid.

## V. CONCLUSIONS

This paper presents a novel power control strategy for voltage unbalance and harmonic compensation in a stand-alone grid. Micrograds have changed the energy distribution sector. New control algorithm allows active power injection and reactive power compensation into the power grid from PV panels. In addition to the fundamental principles, the most recent developments have also been reviewed. In conclusion, discontinuous-based PWM modulation techniques with zero-sequence signal (ZSS) injection are the keys to reduce the switching events and, consequently, power losses corresponding to semiconductor devices. To verify benefits of the new GDPWM control algorithm this paper includes a brief development of a MMC converter, a straightforward analysis of the control strategy and the full simulation of the operation.

The impact of harmonic distortion, efficiency and performance on the power converter has also been mentioned. The results obtained in the simulations have shown the effectiveness of the control system (simulation model has responded satisfactorily to the required active and reactive power flows). A comprehensive set of stationary and dynamic results illustrates that this approach can be an attractive alternative to the classical converter for PV integration to microgrids. It is important to note that in this work is pursuing for a more detailed mathematical model of the system. The main goal has been to work out effective, on-line and simple controls laws, improving the quality of the energy delivered to the power microgrid.

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