

3-Phase Multi-Functional Grid-Tied Inverter for Compensation of Oscillating Instantaneous Power

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Abstract— The primary objective of this paper is to present the basic terms of Conservative Power Theory (CPT) and its applications for compensating instantaneous power oscillations in three-phase three-wire systems. The reference signals for a three-phase multi-functional grid-tied inverter are derived using the instantaneous power and the instantaneous reactive energy terms defined by CPT, having the oscillating power components defined directly in a - b - c coordinates. The compensation method proposed in this study is validated through simulations based on practical power system modeling. The results presented here show the feasibility and singularities of the proposed method.

Keywords—Conservative Power Theory, Instantaneous Power Oscillations, Multifunctional Grid-Tied Inverters, Power Quality, Renewable Energy Sources.

I. INTRODUCTION

The electrical power generation from Renewable Energy Sources (RES) is a topic that has been extensively researched all over the world. Such a trend has been motivated by sustainable energy policies such as credit incentive and tax subsidy, among other reasons [1], [2]. Accordingly, RES recent technologies have been presenting promising solutions for integration of Distributed Energy Resources (DER) [3], [4], such as hybrid/electric vehicles, energy storage and microgrids. In particular, microgrids have been considered an appealing and efficient solution for industrial parks, commercial, rural and residential areas, in addition to several other alternatives considering renewable based DERs [5], [6].

A microgrid is comprised of a set of loads and DER elements that may or may not have energy storage, knowing that such elements are connected to a distribution grid through a Point of Common Coupling (PCC). In general, microgrids are connected through a Power Electronics Interface (PEI), which is usually a voltage source inverter operated by an Energy Management System (EMS) [4]-[7]. Microgrids can operate in either on-grid or off-grid mode, imposing that its infrastructure should be robust and able to switch between these two operation modes smoothly [5], [8].

Also, a microgrid could be implemented as a low voltage distribution system [9]. Therefore, it must be able to supply energy to single- and two-phase (linear or non-linear) loads in

three-phase systems. For instance, possible loads that may be connected to a three-phase three-wire microgrid are computers, lighting reactors, home appliances, battery chargers, among others. Although, the majority of such loads are non-linear, draining unbalanced and distorted currents.

RES connected to microgrids by PEIs usually consist of a DC-DC converter (Buck-Boost), which can track the Maximum Power Point, as well as a DC-AC converter. The DC-AC converter is responsible for maintaining a constant voltage on the DC link and controlling the active power flow at its AC side, in addition to providing power quality ancillary services [10]-[14].

However, some RES, especially PV and wind systems, are highly affected by weather conditions and their physical location within the microgrid. Hence, the energy generated and consumed may vary significantly through time, creating a dynamic and complex power system with high level of interaction between sources and loads. In this context, the main challenges for operating microgrids are the RES intermittency, as well as the variable load consumption, which consequently causes instantaneous power oscillations [15]-[17]. Such variations can cause braking torque oscillations on rotating machines, trigger tie-line power fluctuations [18], also affecting the energy dispatch on wind power generation [19]-[21].

As consequence, it is of importance to mention that power quality issues in a three-wire three-phase microgrid are associated with harmonics, unbalance and instantaneous power oscillations. For example, the nature of the instantaneous power and average power of different load configurations, considering the same rated power, are shown in Fig. 1. Note that the energy oscillation between the load and the source depends on the load configuration. Therefore, different from classic compensation strategies that aim to mitigate current harmonics and unbalance [11]-[14], [22], this paper focuses on the instantaneous power oscillation problem to be suppressed by a three-phase Multi-Functional Grid-Tied Inverter (MFGTI).

To achieve the such goal, this study proposes an innovative use of the instantaneous power and reactive energy terms defined by the Conservative Power Theory (CPT) [23], as a new alternative for the design and control of a three-wire three-phase MFGTI. The proposed control algorithm for

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generating the reference signals for the operation of the inverter is obtained directly in a - b - c coordinates. Thus, the main advantages of the proposed approach are the enhanced efficiency and fast dynamic response of the MFGTI control architecture. Herein, the method is presented and discussed on the basis of simulation results.

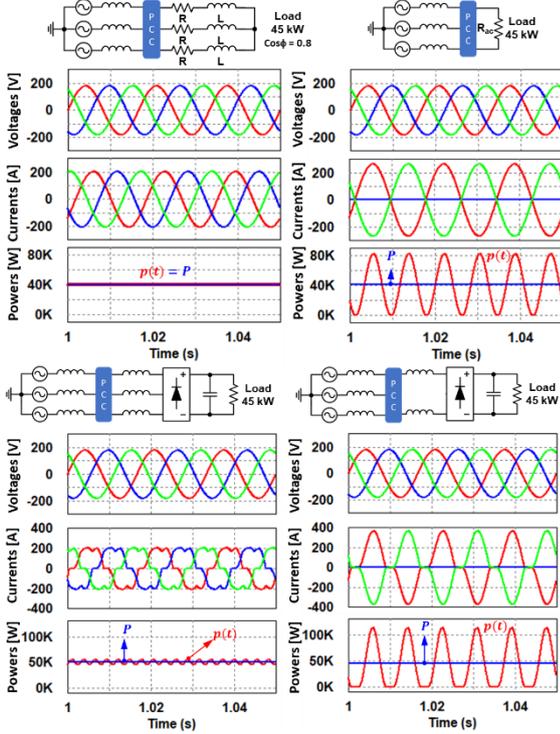


Fig.1 – Time evolution of instantaneous power, $p(t)$ and average power, P to different load configuration with the same nominal power (45 kW).

II. CPT CONCEPTS AND BASIC DEFINITIONS

Consider a set of real electrical quantities, continuous and periodic of period T , with fundamental frequency $f = 1/T$ and angular frequency $\omega = 2\pi f$. As detailed in [23], the CPT proposes an approach in time domain developed entirely based on a - b - c coordinates, on which two instantaneous main terms are defined. First, the instantaneous power term is defined by the scalar product between the voltage (\mathbf{v}) and current (\mathbf{i}) vectors:

$$p(t) = \mathbf{v} \circ \mathbf{i} = [v_a \quad v_b \quad v_c] \circ \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

Secondly, instantaneous reactive energy is defined as:

$$w(t) = \hat{\mathbf{v}} \circ \mathbf{i} = [\hat{v}_a \quad \hat{v}_b \quad \hat{v}_c] \circ \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

where, $\hat{\mathbf{v}}$ is a vector that contains the unbiased integrals of phase voltages. This quantity is calculated by the difference between the time integral and its mean value, as shown in (3).

$$\hat{v}_m = \int_0^t v_m(\tau) d\tau - \frac{1}{T} \int_0^T \left[\int_0^t v_m(\tau) d\tau \right] dt \quad (3)$$

The “ m ” index represents the variables for each phase. Also, according to the CPT, in three-wire three-phase circuits, the phase voltages are measured using a virtual reference point [24].

The mean values corresponding to (1) and (2) are given by (4) and (5):

$$\bar{p} = \frac{1}{T} \int_0^T p(t) dt = \frac{1}{T} \int_0^T (v_a i_a + v_b i_b + v_c i_c) dt = P \quad (4)$$

$$\bar{w} = \frac{1}{T} \int_0^T w(t) dt = \frac{1}{T} \int_0^T (\hat{v}_a i_a + \hat{v}_b i_b + \hat{v}_c i_c) dt = W \quad (5)$$

where P is the active power in Watts e W is the reactive energy in Joules.

Based on the definitions of (4) and (5), the CPT decomposes the load phase currents as the sum of five subcomponents that are: balanced active currents, balanced reactive currents, unbalanced active currents, unbalanced reactive currents, and residual currents [23], [24]. For a sinusoidal voltage operation, independently of balanced or unbalanced characteristics, the active and reactive current components, irrespectively of being balanced or unbalanced related, correspond to a portion of the fundamental current. On the other hand, the residual portion defined by the CPT corresponds to the harmonic components generated by the non-linear loads. These current subcomponents have been satisfactorily applied to generate reference signals for single-phase and three-phase active power filters (APF) [25], [26], as well as for multifunctional grid-tied inverters [11], [12]. Such decompositions provided by the CPT allow selective and oriented identification of different disturbances on a generic load (non-linearities, unbalances and reactive power [24]). Hence, it is possible to set compensation strategies for undesirable currents with high flexibility level.

Since the application of the CPT focusing on the compensation of oscillating powers in three-wire three-phase systems has not yet been explored in literature, the main contribution of this work is settled. It is important to highlight that, although other previously proposed strategies approach the goal of providing constant instantaneous power in electric circuits [15]-[17], their mathematical and physical interpretations, as well as their implementation for the control of MFGTIs, differ from the CPT’s definitions discussed herein. In this context, the following section is presented aiming to analyze the defined power terms within (1), (2), (4) and (5) and their relationship with the generation of control signals for a MFGTI in three-phase three-wire networks.

III. COMPENSATION STRATEGY AND PROPOSED CONTROL ALGORITHM

The strategy to compensate the instantaneous power oscillations by means of the CPT can be obtained through the decomposition of (1) and (2), devising mean and oscillating terms. Therefore, the instantaneous power and reactive energy terms defined in a - b - c coordinates result in (6) and (7), respectively:

$$p(t) = \bar{p} + \tilde{p} \quad (6)$$

$$w(t) = \bar{w} + \tilde{w} \quad (7)$$

where “ \sim ” represents the oscillating components of each instantaneous term. The mean components, which are represented by “ $\bar{\cdot}$ ” can be derived by (4) and (5) and are valid independently of voltage and current waveforms. This means that such approach is valid to be applied for both sinusoidal and non-sinusoidal voltage conditions. Yet, the mean terms

comprised in (6) and (7) can also be derived by low-pass filters, as it is accomplished in alternative methods like the p-q theory [27] or other control algorithms for APFs [15].

The instantaneous power, $p(t)$, represents the useful energy per unit of time that flows from the source to the load (or from the load to the source, if negative). The mean component of $p(t)$, if positive, comprises the energy per unit of time that is transferred from the source to the load. While the oscillating component (\tilde{p}) corresponds to the energy per unit of time which is exchanged between the source and the load. Certainly, the mean value of the oscillating component is zero, but at each instant, it represents a quantity of energy that flows on the electric circuit due to an undesirable current.

In general, the mean component (\bar{p}) can be calculated considering the grid frequency period as in (4). The oscillating component (\tilde{p}), on the other hand, correspond to the components with higher frequencies than the grid's, or it is given by the components of the negative sequence. Furthermore, upon the existence of RES with intermittent and unpredictable behavior, \tilde{p} can also be found within harmonic frequencies, unbalanced loads, or due to resonances triggered by single- or two-phase converters connected to three-wire three-phase circuits. Particularly, in three-phase electric circuits, with or without neutral wire, where voltages and currents consist only of positive sequence and fundamental components, the energy transfer is unidirectional, usually flowing from source to load. In this case, the instantaneous power contains just the mean component ($p(t) = \bar{p} = P$).

Additionally, there are other specific scenarios on which energy is transferred unidirectionally from source to load. For instance, it occurs when voltages and currents are in phase, balanced, and present the same harmonics (common harmonics). In any other situation, if voltages and currents are distorted (i.e., presenting uncommon harmonics) or with unbalanced components, the instantaneous power will present mean and oscillating components with the bidirectional flow.

A. Reference Signal Generation for Compensation of Instantaneous Power Oscillations

With the active power and reactive energy portion defined in (6) and (7), two instantaneous current components, \mathbf{i}_p and \mathbf{i}_w , can be defined as:

$$\mathbf{i}_p = \frac{\bar{p}}{v_{abc}^2} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + \frac{\tilde{p}}{v_{abc}^2} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (8)$$

$$\mathbf{i}_w = \frac{\bar{w}}{\hat{v}_{abc}^2} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} + \frac{\tilde{w}}{\hat{v}_{abc}^2} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} \quad (9)$$

where $v_{abc}^2 = v_a^2 + v_b^2 + v_c^2$ and $\hat{v}_{abc}^2 = \hat{v}_a^2 + \hat{v}_b^2 + \hat{v}_c^2$ are the collective instantaneous values of voltage and unbiased integrals of voltage, respectively. The bold variables represent vectors.

Therefore, the current vectors associated with instantaneous terms [$p(t)$ e $w(t)$] can be decomposed into two subcomponents:

$$\mathbf{i}_p = \mathbf{i}_{\bar{p}} + \mathbf{i}_{\tilde{p}} \quad (10)$$

$$\mathbf{i}_w = \mathbf{i}_{\bar{w}} + \mathbf{i}_{\tilde{w}} \quad (11)$$

The oscillating components ($\mathbf{i}_{\tilde{p}}$ e $\mathbf{i}_{\tilde{w}}$) represent the harmonic components and/or the unbalanced current resulting from voltage and current uncommon harmonics and unbalanced voltages. These oscillating portions do not

contribute to the active power (P) or to the reactive energy (W). Hence, $\mathbf{i}_{\tilde{p}}$ e $\mathbf{i}_{\tilde{w}}$ are responsible for the instantaneous power oscillations in the electric circuit, as well as for any additional losses.

From the load point of view, the decomposed portions shown in (10) and (11) do not represent any specific load behavior or characteristic; only on the condition of sinusoidal and balanced voltages, $\mathbf{i}_{\bar{p}}$ e $\mathbf{i}_{\bar{w}}$ coincide with active and reactive balanced currents defined by CPT.

Since oscillations on reactive energy and instantaneous power can be caused by voltage and current distortions, as well as by unbalance on voltage and current, the reference signals for compensation can be represented by the sum of $\mathbf{i}_{\bar{w}}$, $\mathbf{i}_{\tilde{p}}$ e $\mathbf{i}_{\tilde{w}}$ as presented in (12).

$$\begin{bmatrix} i_{a-APF} \\ i_{b-APF} \\ i_{c-APF} \end{bmatrix} = \begin{bmatrix} i_{a-\bar{w}} \\ i_{b-\bar{w}} \\ i_{c-\bar{w}} \end{bmatrix} + \begin{bmatrix} i_{a-\tilde{p}} \\ i_{b-\tilde{p}} \\ i_{c-\tilde{p}} \end{bmatrix} + \begin{bmatrix} i_{a-\tilde{w}} \\ i_{b-\tilde{w}} \\ i_{c-\tilde{w}} \end{bmatrix} \quad (12)$$

It is noted in (12) that such references for compensation purposes can be applied in a selective manner, where the sum of its components $\mathbf{i}_{\tilde{p}}$ e $\mathbf{i}_{\tilde{w}}$ is related to the oscillations and $\mathbf{i}_{\bar{w}}$ is associated with the reactive energy (power) flow in the system. Hence, the components ($\mathbf{i}_{\tilde{p}} + \mathbf{i}_{\tilde{w}}$) and ($\mathbf{i}_{\bar{w}}$) can be compensated independently by the MFGTI, or even by the combination of capacitor banks, which would compensate $\mathbf{i}_{\bar{w}}$, and the MFGTI ensuring compensation of $\mathbf{i}_{\tilde{p}} + \mathbf{i}_{\tilde{w}}$. Therefore, since the main goal of this study is to compensate the oscillations, the sum of the oscillating components will be taken as reference, in other words, $\mathbf{i}_{APF} = \mathbf{i}_{\tilde{p}} + \mathbf{i}_{\tilde{w}}$.

B. Reference Signal Generation to Inject Active Power

The current reference signal for the injection of the energy generated by a Local Energy Source (LES) is created based on the synthesis of sinusoidal currents. According to this strategy, the injected current waveform should match the waveform of the positive sequence fundamental component of the PCC voltages (v_{m1}^+). As discussed in [11], such strategy guarantees a smaller distortion level in the current. Thus, the active current reference \mathbf{i}_{LES} of the MFGTI is determined by (13).

$$\mathbf{i}_{LES} = \frac{P_{LES}}{V_1^2} \begin{bmatrix} v_{a1}^+ \\ v_{b1}^+ \\ v_{c1}^+ \end{bmatrix} = G_{LES} \begin{bmatrix} v_{a1}^+ \\ v_{b1}^+ \\ v_{c1}^+ \end{bmatrix}, \quad (13)$$

where G_{LES} is the equivalent conductance of the multifunctional converter and P_{LES} is the liquid power generated from the LES, which should be injected into the grid:

$$P_{LES} = \frac{1}{T} \int_0^T v_{DC}(t) i_{DC}(t) dt. \quad (14)$$

The fundamental voltage component at the converter point of coupling (v_{m-1}) can be obtained using a Phase Locked Loop (PLL) or through a low-pass filter with a narrow bandwidth tuned into the grid frequency. Considering that the grid frequency variation is relatively small, a low-pass filter was chosen to attain v_{m-1} , followed by the RMS (V_{m-1}) value calculation.

C. Reference Signal Generation for the Three-Phase Multifunctional Converter

Considering the reference signal shown in (12) and (13), the final current reference (\mathbf{i}_{ref}^*) that is effectively synthesized by the MFGTI is given by:

$$\mathbf{i}_{ref}^* = \mathbf{i}_{LES}^* - \mathbf{i}_{APF}^* \quad (15)$$

If the multifunctional converter was to operate only as a PEI, without doing the compensation of the instantaneous power oscillations, the signal \mathbf{i}_{APF}^* would be zero and the converter would only inject the energy generated by the LES into the grid. On the other hand, as the component $\mathbf{i}_{\bar{w}}$ does not contribute to the instantaneous power oscillation, to completely compensate the instantaneous power oscillations it is enough to assign the terms $\mathbf{i}_{\bar{p}} + \mathbf{i}_{\bar{w}}$ to the compensation reference, as:

$$\mathbf{i}_{ref}^* = \mathbf{i}_{LES}^* - \mathbf{i}_{\bar{p}}^* - \mathbf{i}_{\bar{w}}^* \quad (16)$$

IV. CONTROL SYSTEM MODELLING

A modelling method and control design for three-phase converters using an APF is presented in reference [28] and the same approach is used for the MFGTI presented in this study. The system presented in Fig. 2 summarizes the topology of the adopted electrical circuit and converter. Also, the main electrical system parameters are shown in Table I. Because the system presented in Fig. 2 is a three-wire circuit with no neutral, the mesh control can be achieved considering the voltage and current values in only two phases of the three-phase system. For instance, for the converter, it is sufficient to control currents i_{Fa} and i_{Fb} , since the current i_{Fc} is related to the previous currents, being $i_{Fc} = -i_{Fa} - i_{Fb}$. Regarding the virtual point voltages, they can be obtained from the line voltage [24], according with (17). Thus, to v_{ab} e v_{bc} could be measured and the third line voltage component is derived applying Kirchoff's voltage law, having $v_{ca} = -(v_{ab} + v_{bc})$, for instance.

TABLE I. THREE-PHASE CONVERTER AND SYSTEM PARAMETERS.

Parameter	Value	Parameter	Value
Grid, V_{Line}	220 V / 60 Hz	$L_G; R_G$	0.25 mH; 0.1 Ω
P_{LES}	2.4 kW	$L_1; R_1$	0.5 mH; 10 m Ω
C_0	3,3 μ F	$L_2; R_2$	0.5 mH; 10 m Ω
R_x, L_x	5 Ω ; 40 mH	L_z	1 mH
L_y, R_y	70 mH; 30 Ω	R_z, C_z	50 Ω ; 470 μ F

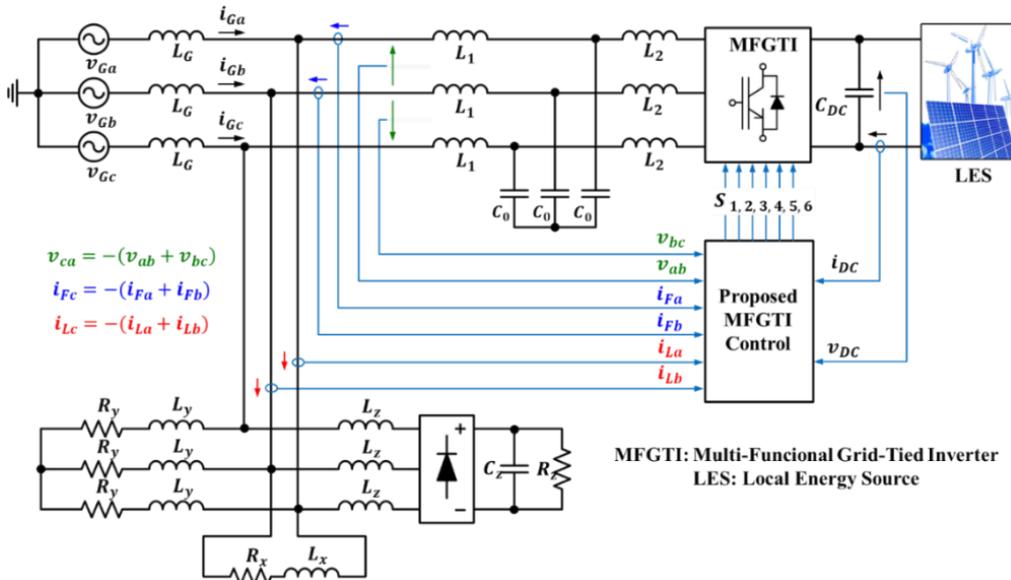


Fig.2 – Three-phase MFGTI connected to the electric grid.

$$\begin{aligned} v_a &= \frac{1}{3}(v_{ab} + v_{ac}) \\ v_b &= \frac{1}{3}(v_{ba} + v_{bc}) \\ v_c &= \frac{1}{3}(v_{cb} + v_{ca}) \end{aligned} \quad (17)$$

The converter control system comprises two main control loops. The first is a fast loop used to control the converter output current, whereas the second is a voltage control loop that presents a slow dynamic response. The DC bus control keeps the energy balance between the power delivered to the system at the converter's output side and the power at its DC link [29]. Fig. 3 shows the control strategy adopted with the control loops proposed for the MFGTI.

The current control is based on a proportional resonant controller and another resonant harmonic controller (PR+HC) [30], [31], as:

$$G_C(s) = K_C + \sum_{h=1,3,5,\dots,11} \frac{2K_{IPR}\omega_{cPR}s}{s^2 + 2\omega_{cPR}s + (h\omega_o)^2} \quad (18)$$

In (18), h is the harmonic order, ω_o is the grid fundamental frequency and K_C , K_{IPR} , ω_{cPR} are the proportional gain, integral gain and a resonant frequency band pass controller, respectively. The K_{IPR} value is chosen to produce a high gain on harmonic frequencies and ω_{cPR} should be designed to compensate harmonic frequencies and is supposed to be small to amplify the compensator selectivity.

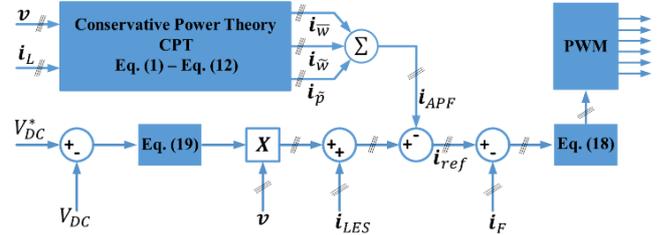


Fig.3 – Proposed multifunctional structure block diagram.

The voltage controller used to maintain constant the DC link voltage is a proportional-integral (PI) regulator and it is given by (19):

$$PI_{DC}(s) = K_{P_{DC}} + \frac{K_{I_{DC}}}{s} \quad (19)$$

where $K_{P_{DC}}$ is the controller proportional gain, while $K_{I_{DC}}$ is the integral gain. The MFGTI was designed with a switching frequency of 20 kHz. Table II shows the adopted values for the voltage and current controllers. The converter DC link voltage is adjusted to 400 V.

$K_c = 2$	$K_{I_{PR}} = 100$
$\omega_{c_{PR}} = 6,28$ [rad/s]	$\omega_o = 377$ [rad/s]
$K_{P_{DC}} = 5$	$K_{I_{DC}} = 50$

V. SIMULATION RESULTS

In order to validate the compensation strategy and the proposed control algorithm for the three-phase MFGTI, the circuit shown in Fig. 2 was simulated using PSIM[®]. The circuit comprises an electronic converter (DC-AC) with a LCL output filter, a three-phase non-linear unbalanced load and the electric grid.

The main simulation goal is to validate the proposed method to achieve a constant instantaneous power, and at the same time inject, active power into the grid. The system operation dynamic is described by voltages, currents, power terms and instantaneous reactive energy in different measuring points at the grid, load and converter, respectively. Following, the simulation results are presented for two distinct scenarios.

A. Scenario 1: MFGTI injecting only active power

In this first scenario, the MFGTI is operated to function only as a power electronic interface (PEI). This simulation result is shown in Fig. 4. It can be seen that initially at $t < 0,6$ s, the converter currents (i_{Fa} , i_{Fb} e i_{Fc}) are zero and the grid currents (i_{Ga} , i_{Gb} e i_{Gc}) are highly distorted and unbalanced. With the actioning of the PEI function at $t > 0,6$ s, the converter currents are sinusoidal and synchronized with the PCC voltages. Hence, the mean grid component, \bar{p}_G (active power), decreases while the grid currents continue to be distorted and unbalanced. In addition, consequently, the oscillating components \tilde{p}_G e \tilde{w}_G present a non-sinusoidal oscillation and continue to flow through the grid.

B. Scenario 2: MFGTI injecting active power and compensating power oscillations

In this second scenario, the active power filter (APF) ancillary service is added to the MFGTI. The simulation result can be seen in Fig. 5. Before the APF function is activated ($t < 1,2$ s) it can be observed that the harmonic distortion and current unbalance create a non-sinusoidal oscillation at the \tilde{p}_G e \tilde{w}_G components. In addition, it can be seen a slightly distortion and voltage unbalance at the PCC, caused by the unbalanced non-linear load. After starting the APF service in the MFGTI at $t > 1,2$ s, the current unbalance as well as the harmonics generated by the non-linear load (residual component) that are present in the grid are compensated, which results in the elimination of all oscillating components (\tilde{p}_G e \tilde{w}_G); therefore, improving the voltage waveforms at the PCC. The compensation results can also be observed at the grid current waveform that becomes sinusoidal and balanced.

However, the grid current is still lagging the voltage because of the average reactive energy (\bar{w}_G), which is not being compensated.

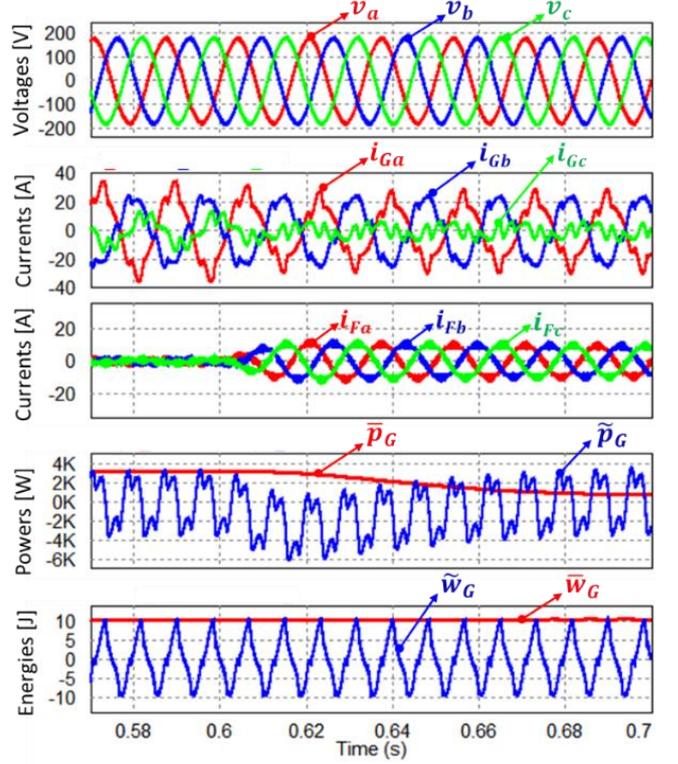


Fig. 4. Simulation results when the MFGTI is injecting only active power into the grid (Scenario 1).

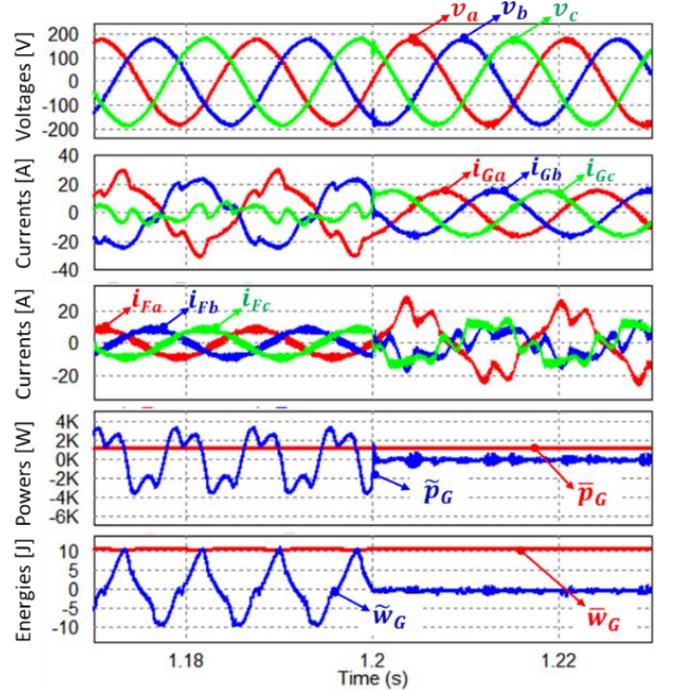


Fig. 5. Simulation results when the MFGTI is injecting active power and compensating the oscillations (Scenario 2).

VI. CONCLUSIONS

It was presented in this paper a strategy of using grid-connected multifunctional power electronic converters for injecting active power into the grid and compensating instantaneous power oscillations. The proposed control is based on instantaneous and average terms ($p(t)$, $w(t)$, $\bar{p}(t)$ and $\bar{w}(t)$) of the Conservative Power Theory (CPT).

As shown in the simulation results, the proposed control strategy allows not only injection of active power, but also supports power system operation at constant instantaneous power, $p(t) = \bar{p}(t)$, even under different linear/non-linear unbalanced load configurations. This feature is extremely important since the instantaneous power oscillations are undesirable in any power system due to rotating electric machines deterioration, and operation issues regarding power quality, especially on scenarios of weak electric grids such as microgrids.

Furthermore, considering the compensation results presented, future work is needed to verify the feasibility of the proposed strategy under distorted and unbalanced conditions, not only at PCC, but also at the voltage source (grid). Thus, power system operation at constant instantaneous power is expected even under adverse conditions. Yet, extensions of this work intend to further evaluate the singularities of the methodology proposed, exploring its advantages and disadvantages, when compared to other methods in the literature.

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