Selective Power Conditioning in Two-Phase Three-Wire Systems Based on the Conservative Power Theory

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***Abstract* -- AC power conditioners in electric power systems have been extensively explored in the literature based on approaches mainly focused on single- and three-phase wiring topologies, remaining a significant gap in regard to applications suitable for two-phase three-wire circuitry. Therefore, this work demonstrates that the Conservative Power Theory can be employed to generate the proper reference signals for an active power filter in two-phase three-wire networks. This methodology allows to selectively synthesize reference signals in a flexible manner, providing reactive power compensation, mitigation of unbalance and harmonic currents, as well as contributing to the reduction of neutral current at point of common coupling. The proposed strategy, its implementation, and the control design of a three-leg active power filter are discussed in this paper through simulation results, demonstrating the particularities and advantages of this approach.**

***Index Terms* -- Active Power Filter, Conservative Power Theory, Harmonics, Power Quality, Two-phase Three-wire, Unbalance.**

I. INTRODUCTION

The need for power quality enhancement in electrical systems has been, for a long time [1], [2], driving technology innovations and the development of methodologies able to provide the means for achieving more robust and reliable power grids. For instance, the undesired existence of reactive power, unbalance and harmonic currents in electrical circuits, as well as neutral currents, have boosted the spreading and adoption of passive filters, later evolving to the use of active power filters (APFs) and multifunctional inverters [1]-[3].

Considering applications formulated for single- and three-phase power systems, several strategies have been extensively proposed and studied [3]-[6], therefore, being able to prove their effectiveness through the improvement of power quality indexes. Nonetheless, when it comes to two-phase systems with neutral conductor, herein named two-phase three-wire (*2Φ3w*), there still remains a gap in the literature regarding the employment of methodologies able to accurate mitigate undesired power quality (PQ) issues. Although *2Φ3w* systems are not widely encountered, such topology is still present in motor applications [7], railway traction power supplies [8], residential installations around the world [9], [10], as well as on specific topologies of microgrids [11]. Thus, it is of great importance to develop methodologies that can characterize PQ concerns in *2Φ3w* circuits, while providing ways of mitigating their related undesired issues.

Previous researches focusing on *2Φ3w* networks are found in the literature, mainly discussing some methodologies capable of synthesizing reference signals to active power conditioners [9], [10], [12]-[16]. For instance, in [12], an adaptation of the Instantaneous Power Theory (p-q theory) is proposed for *2Φ3w* systems to identify power components, and to generate reference signals for a three-leg APF, striving for the mitigation of reactive terms, harmonics and load imbalances. In this case, adapted linear transformations are used to translate natural frame voltages and currents onto the $\alpha\beta$ reference frame, later defining average and oscillating powers that diverge in meaning from the traditional p-q theory [4]. Alternative methods also formulated through the p-q theory focus on the control of *2Φ3w* converters driven as two independent single-phase APFs [13], considering adaptations on the single-phase p-q theory [14], or with superposition of two simultaneous operations to additionally mitigate neutral currents using the indirect sine multiplying current control technique [15].

Other approaches propose active power conditioning in *2Φ3w* circuits based on the exchange of powers between the existing phases, using the DC link of two-phase back-to-back converters [9], multilevel converters [16] or quasi-Z-source converters [17]. However, such approaches do not present novelties focused on the decomposition of currents or power terms, neither characterizing their effects. Thus far, although in [11] circuit analysis based on symmetrical components are proposed for a new topology of two-phase microgrids, which presents two voltages in quadrature, it mainly targets the characterization of powers and harmonics, not directly presenting methods to intervene on power quality issues, nor being directly applied to *2Φ3w* systems.

Hence, it is remarked that the existence of methodologies able to provide the analysis of power and current components drawn in *2Φ3w* systems, being concomitantly able to be applied for PQ enhancement, is still an underexplored issue in the literature. In this work, the use of the Conservative Power Theory (CPT) [18] is proposed as an important contribution, exploring its ability to characterize *2Φ3w* systems to provide accurate references for compensation of reactive, harmonic and unbalance current terms, as well as reducing the neutral currents. Moreover, the authors have not found in the recent literature studies that use the CPT as a methodology for current and power decomposition and its application for PQ improvement in *2Φ3w* systems. Therefore, a three-leg shunt APF is designed to perform power conditioning in a low-voltage grid, enduring in a selective way different operational goals upon the existence of unbalanced and nonlinear loads.

This work is organized as follows. The main features of the CPT for the *2Φ3w* systems are defined and discussed in Section II. The adopted circuitry and control scheme of the three-leg APF is presented in Section III, having the simulated results of active compensation shown in Section IV. Conclusions are then presented to highlight the effectiveness of the methodology.

II. CONSERVATIVE POWER THEORY IN TWO-PHASE SYSTEMS

The Conservative Power Theory (CPT) [18] is a time-domain (*abc* frame) based methodology that provides means for analyzing modern electrical circuits, being applied to single- or poly-phase systems with periodic quantities, regardless whether it is under sinusoidal, asymmetrical or distorted voltage conditions. Current and power components are decoupled based upon the conservativeness of the active power and reactive energy terms devising interpretation for physical phenomenon existing in a circuit [19]. The proposed definition of power terms and corresponding decomposed current components for the *2Φ3w* systems are discussed as follows.

A. Power Terms and Decomposed Current Components

Firstly, focusing on the conservative terms (power and energy), and also knowing that instantaneous and RMS quantities are at this point described, respectively, by lowercase and uppercase variables, the active power (P) defined in a *2Φ3w* circuit is given by (1). In such definition, v_m stands for the voltage of phase m (a and b) in relation to the neutral conductor, i_m is the line current circulating through this same phase, and T is the period of these signals.

$$P = \frac{1}{T}\sum_{m=a}^{b}\int_{0}^{T} v_m i_m dt = \frac{1}{T}\int_{0}^{T}(v_a i_a + v_b i_b)dt \tag{1}$$

Similarly, the reactive energy (W) is defined by (2), where $\hat{v}_m$ is the unbiased-time integral of voltage, which is calculated by attaining the integral of v_m and removing its mean value [18]. Consequently, the reactive power (Q) can be defined as (3), having ω as the angular line frequency.

$$W = \frac{1}{T}\sum_{m=a}^{b}\int_{0}^{T} \hat{v}_m i_m dt = \frac{1}{T}\int_{0}^{T}(\hat{v}_a i_a + \hat{v}_b i_b)dt \tag{2}$$

$$Q = \omega \cdot W \tag{3}$$

Considering P and W, the currents through the m-phase can be decomposed into orthogonal terms related to active and reactive components, considering both balanced and unbalanced load operations, in addition to a remaining component (void current), which stands for the distortion currents. Considering the subscripts a, r, and v, respectively for the active, reactive and void terms, and also the superscripts b and u for the balanced and unbalanced features of such parcels, the instantaneous current decomposition can be rewritten by (4). Note that, from (4) the void current of each m-phase is attained from (5).

$$i_m = i_{am}^{b} + i_{rm}^{b} + i_{am}^{u} + i_{rm}^{u} + i_{vm} \tag{4}$$

$$i_{vm} = i_m - (i_{am}^{b} + i_{rm}^{b} + i_{am}^{u} + i_{rm}^{u}) \tag{5}$$

Based on the RMS collective value of the voltage ($\mathbf{V}_{col}$) and P, the balanced active currents can be attained from (7). Analogously, upon the calculation of the RMS collective value of the unbiased voltage ($\hat{\mathbf{V}}_{col}$) and W, the balanced reactive currents are given by (8). The unbalanced active currents take into account the difference between the phase conductance and the equivalent conductance as seen in (9), where V_m and P_m are, respectively, the RMS phase voltage and active power of m-phase. Similarly, the unbalanced reactive currents are giving by (10).

$$\mathbf{V}_{col} = \sqrt{V_a^2 + V_b^2} \quad \text{and} \quad \hat{\mathbf{V}}_{col} = \sqrt{\hat{V}_a^2 + \hat{V}_b^2} \tag{6}$$

$$i_{am}^{b} = \frac{P}{\mathbf{V}_{col}^2}\cdot v_m, \quad m = a, b \tag{7}$$

$$i_{rm}^{b} = \frac{W}{\hat{\mathbf{V}}_{col}^2}\cdot \hat{v}_m, \quad m = a, b \tag{8}$$

$$i_{am}^{u} = \left(\frac{P_m}{V_m^2} - \frac{P}{\mathbf{V}_{col}^2}\right)\cdot v_m, \quad m = a, b \tag{9}$$

$$i_{rm}^{u} = \left(\frac{W_m}{\hat{V}_m^2} - \frac{W}{\hat{\mathbf{V}}_{col}^2}\right)\cdot \hat{v}_m, \quad m = a, b \tag{10}$$

Since the abovementioned current terms are decoupled, selective current references for compensation purpose can be generated with respect to any of these terms. Note that, these terms are being straight obtained in the *abc* frame, then the CPT in *2Φ3w* systems also eliminate the need for any further axis transformations, on the contrary of [4], [12]. Therefore, these decomposed current terms are used as references for the local control of APFs, aiming at flexibly providing mitigation of undesired currents existing in the system, such as reactive and harmonic compensation, in addition to unbalances minimization.

The CPT also provides definitions for power terms, leading to the possibility of performing further characterization of the electrical circuit features. The apparent power definition is given by the product between the collective voltage and currents of the circuit as in (11). Note that $\mathbf{I}_{col}$ can be calculated by (12) since the decomposed current terms are orthogonal to each other, as aforementioned.

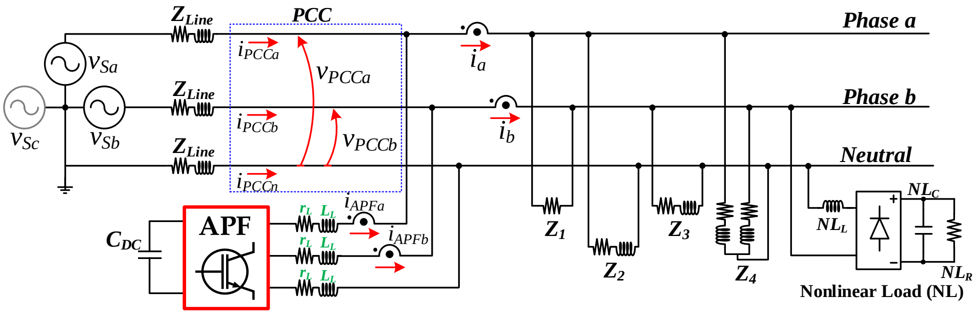

Fig. 1. Two-phase three-wire circuit with loads and three-leg APF used on the simulation results.

TABLE I. SYSTEM PARAMETERS

Parameter		Value
Grid Nominal Voltage (v_{sm}): phase-neutral		127 V / 60 Hz
Line Impedances (Z_{Line}): per phase		0.018 + j0.037 Ω
Resistive Load (Z_1)		22 Ω
Resistive-Inductive Load (Z_2)		1 + j6.032 Ω
Resistive-Inductive Load (Z_3)		12 + j4.524 Ω
Resistive-Inductive Load (Z_4)		18 + j4.5244 Ω
Nonlinear Load (*NL*)	NL_L	+j1.885 Ω
	NL_C	-j5.643 Ω
	NL_R	10 Ω

TABLE II. APF PARAMETERS

Parameter		Value
Nominal Power (A_{APF})		25 kVA
DC Link Voltage (V_{DC})		500 V
Filter Resistance (r_L): per phase		0.095 Ω
Filter Inductance (L_L): per phase		2.5 mH
Switching (f_{sw}) & Sampling (f_s) Frequencies		12 & 24 kHz
Current Controller	Proportional Gain (KP_i)	5.890
	Resonant Gain (KP_h)	884.683
Voltage Controller	Proportional Gain (KP_v)	7.323
	Integral Gain (KI_v)	167.485

$$A^2 = \boldsymbol{V}_{col}^2 \boldsymbol{I}_{col}^2 = P^2 + Q^2 + N^2 + D^2 \tag{11}$$

$$\boldsymbol{I}_{col}^2 = \left(\boldsymbol{I}_{a\,col}^b\right)^2 + \left(\boldsymbol{I}_{r\,col}^b\right)^2 + (\boldsymbol{I}_{col}^u)^2 + (\boldsymbol{I}_{v\,col})^2 \tag{12}$$

The power component *D* represents the distortion power and stands for the load nonlinearities (harmonics) existing in the circuit. While *N* is the unbalance power, which is comprised of a term respective to unbalances caused by loads as in [18].

$$D = \boldsymbol{V}_{col} \boldsymbol{I}_{v\,col} \tag{13}$$

$$N = \boldsymbol{V}_{col} \sqrt{(\boldsymbol{I}_{a\,col}^u)^2 + (\boldsymbol{I}_{r\,col}^u)^2} = \boldsymbol{V}_{col} \boldsymbol{I}_{col}^u \tag{14}$$

III. GRID TOPOLOGY AND SELECTIVE APF CONTROL STRATEGIES

A. *2Φ3w Grid Infrastructure*

Two-phase three-wire grids, in general, are derived from three-phase four-wire systems, on which two conductors are devised by AC power supplies with phase voltages shifted, and the third wire is the neutral conductor. This system is shown in Fig. 1, presenting equal line impedances per wire (Z_{line}) and several loads (Z_x, x = 1,2,3,4) distributed among conductors. Due to the intention of demonstrating the operationally of the proposed methodology in this work, which comprises the characterization of reactive, unbalance and harmonic effects, such loads are composed of passive elements and nonlinear component. The system parameters are summarized in Table I. A three-leg APF presenting resistive-inductive output filter is coupled to the PCC to provide accurate current quality conditioning. Its parameters are presented in Table II, and the control approach using the CPT for its application in *2Φ3w* systems is presented in the following sections.

B. *Three-leg APF Control Design*

For the proposed system, it is required to employ a three-leg APF to inject currents that perform particular interventions in regard to the desired current quality at the grid side. To synthesize compensation currents for the APF, a control scheme was adopted as demonstrated in Fig. 2. Since the converter presents three legs, only two legs are required to be controlled [20], which are herein defined to be the ones responsible for the currents flowing through the APF's phases *a* and *b*. The nominal apparent power of the converter (A_{APF}) was defined in order to allow full compensation of undesired currents.

The CPT's decomposition defines the reference signals of the APF ($i^*_{APF_m}$). As seen in Fig. 2, such references are calculated by the definitions described in Section II, with the phase voltages and currents at PCC as inputs, being then summed up depending on the compensation goal (e.g., different simulated cases which are later discussed and explained). The APF operates under a multi-loop control methodology presented in [21], with an outer voltage loop responsible to maintain constant the voltage at its DC bus (V_{DC}), as well as with an inner current loop that controls the currents injected by the APF. The former loop is devised considering a proportional-integral (PI) controller given by (15), and the latter uses proportional-resonant (PRes) controllers calculated by (16) and described in [22]. In such scheme, the reference *s** shown in Fig. 2 is defined to balance the power between the DC and AC sides of the converter [21].

$$G_{PI}(s) = KP_v + \frac{KI_v}{s} \tag{15}$$

$$G_{PRes}(s) = KP_i + \sum_{h=1,3,5,7} \frac{2.KI_h.s}{s^2 + (h.\omega_o)^2} \tag{16}$$

Double-update mode i.e., with sampling frequency (f_s) twice the switching frequency (f_{sw}), was adopted for the modeling and calculation of the controllers gains as in [22]. The PRes controllers were designed to damp the fundamental, 3rd, 5th and 7th harmonic orders, following a cut-off frequency of f_{sw}/10. The frequency response of the APF's current control is depicted in Fig. 3, and the respective controller gains are shown in Table II.

IV. SIMULATION RESULTS

To assess the proposed selective compensation provided by the CPT with a three-leg APF in a *2Φ3w* grid, four particular cases with different compensation goals were selected to demonstrate the feasibility and selectivity of the proposed approach. Such cases focus on enhancing current quality at the PCC, respectively, through the mitigation of reactive currents (case I), unbalance components (case II), harmonics (case III), and finally diminishing all these three undesired current components at once (case IV).

Initially, as shown in Fig. 4 up to 1.2 s, both PCC voltages and currents, as well as the components being injected by the APF, are demonstrated when no current quality intervention is provided (i.e., APF does not inject currents and the PCC current is given by the amount drawn by the loads). It can be noted that different and distorted currents are circulating in phases *a*, *b* and on the neutral conductor. For instance, although the currents being phase-shifted in relation to their corresponding phase voltages, the one in phase *a* is nearly sinusoidal due to the nonexistence of nonlinear loads at this phase. Contrariwise, the current in phase *b* is distorted with a total harmonic distortion (THD_i) value of 16.17 %. An analysis of the harmonic spectrum of the PCC currents is also shown in Fig. 8-a, proving that phase *b* current presents significant amplitude for 3rd harmonic order. Small amplitudes for the 5th, 7th and 9th order harmonics also exist, different from phase *a* current, which contains only the fundamental components. Moreover, as expected from Kirchhoff's Law, the neutral current sums up phase *a* and *b* currents, resulting in distorted waveform (i.e., THD_i of 15.28 %) with similar harmonic pattern, as well as high amplitude for the fundamental component.

Then, after 1.2 s, the first compensation goal is set for the APF (case I), aiming at injecting at each phase only the balanced reactive current components decomposed by the CPT i.e., $i^*_{APF_m} = -\,i^b_{r_m}$. As seen in Fig. 4, the APF synthesizes balanced sinusoidal currents for both phases plus neutral, aiming at reducing the existent phase shift between voltages and currents at the PCC. Such expected intervention indeed occurs, and since $i^u_{r_m}$ is small in relation to the other remaining current terms, it results in PCC currents that are practically in-phase with their corresponding phase voltages. Nevertheless, since only balanced reactive currents (fundamental components) are being compensated by the APF, distorted waveforms remain in phase *b* and neutral currents. From Fig. 8-b it becomes clear that the fundamental component of currents were reduced in relation to Fig. 8-a. Besides, note that the harmonic content was not mitigated maintaining the previous pattern.

A new objective is determined for the APF in Fig. 5 (case II), targeting the suppression of unbalance current terms i.e., $i^*_{APF_m} = -i^u_m = -(\,i^u_{a_m} + i^u_{r_m})$. As aforementioned, the neutral current presented fundamental component with the highest amplitude when no compensation was performed. Therefore, the APF injects into the neutral conductor a current with considerable amplitude. This results in PCC currents with balanced fundamental components, as shown in Fig. 8-c. Again, harmonics are still circulating in the circuit distorting the current waveforms. Thus far, it is important to highlight that, since no balanced reactive currents were compensated by the APF, the PCC currents remain phase-shifted in relation to the voltages. It is important to underline that this system is considered balanced when phases *a* and *b*

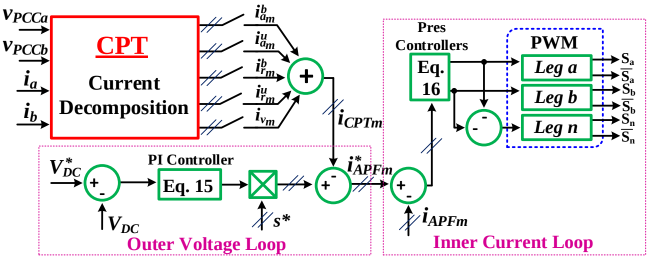

Fig. 2. Reference generation and control scheme of the three-leg APF.

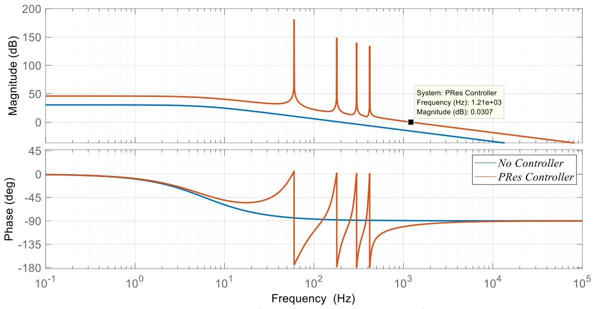

Fig. 3. Frequency response of the current loop of the three-leg APF.

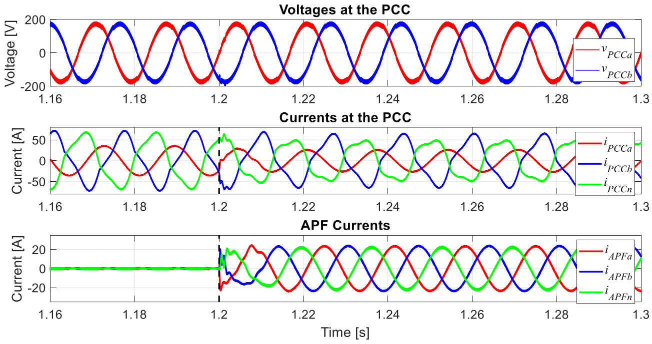

Fig. 4. APF injecting reactive currents parcels (reactive compensation).

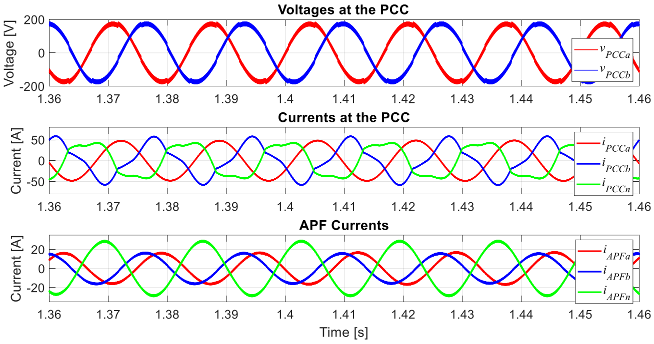

Fig. 5. APF injecting unbalance currents (unbalance compensation).

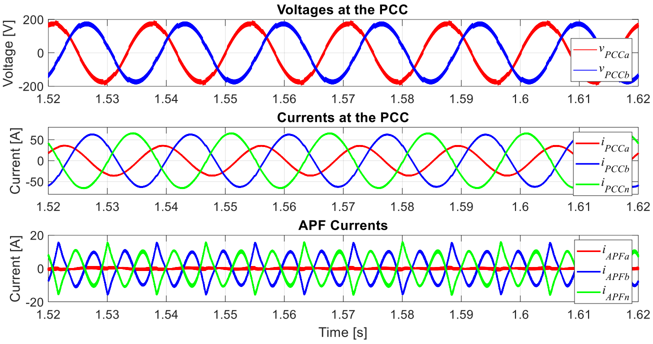

Fig. 6. APF injecting void currents (harmonics compensation).

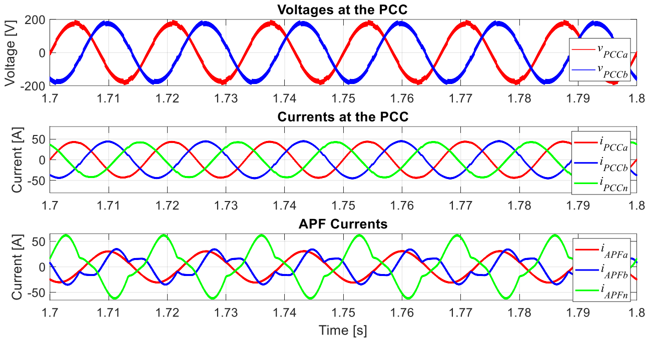

Fig. 7. APF injecting nonactive currents (compensation of reactive, unbalance and harmonics).

conductances and susceptances are equal to the respective values when an equivalent circuit is calculated.

Harmonics are detrimental to power systems, therefore, diminishing their presence can considerably improve power quality. Following such premise, case III imposes the APF to compensate the void currents i.e., $i^{*}_{APF_m} = -i_{v_m}$. Fig. 6 demonstrates that the APF provides highly distorted currents for phase *b* and neutral, resulting in nearly sinusoidal currents at the PCC. Note in Fig. 8-d that all harmonic components were practically compensated, resulting in THD_i for phase *b* and neutral of 1.98 % and 1.76 %, respectively. Due to the selective compensation strategies defined by the CPT, the remaining PCC currents present active, reactive and unbalance components, which justifies the phase-shifted and unbalanced currents with different amplitudes at the fundamental frequency in Fig. 8-d. Furthermore, note that, in relation to Fig. 8-a, the fundamental components were not affected by the harmonic compensation.

Finally, the last strategy consists of a scenario in which all the undesired current components are compensated by the APF (case IV), aiming at imposing only in-phase fundamental currents at the PCC. To achieve such goal, the reference current signals for APF are obtained from the nonactive currents i.e., $i^{*}_{APF_m} = -i_m + i^{u}_{a_m} + i^{b}_{r_m} + i^{u}_{r_m} + i_{v_m} = -i_{na}$. The result of the nonactive currents compensation is shown in Fig. 7. It can be noted that, since the APF compensates the reactive, unbalance and distorted current terms, the remaining current through the PCC is nearly sinusoidal with THD_i of 1.19 %, 1.40 % and 1.55 % respectively for phases *a*, *b* and neutral. From Fig. 8-e the balanced feature of the PCC currents is reinforced presenting fundamental components with similar amplitudes, and the harmonics appearing practically diminished. A final remark is made in regard to the neutral current. It can be noted that, besides having its distortion eliminated, the amplitude of its fundamental component is reduced by about 33 %, in relation to the case where no compensation is performed.

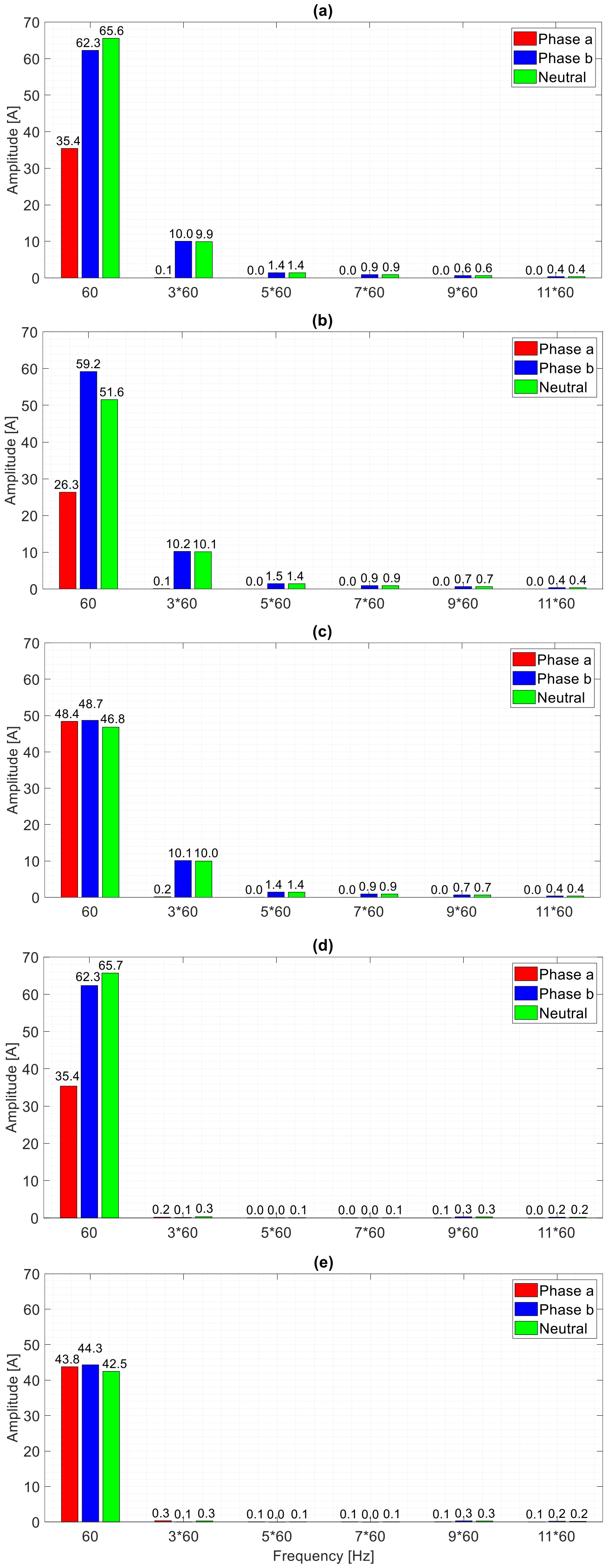

Fig. 8. FFTs of PCC currents upon different compensation goals: (a) no intervention; (b) reactive; (c) unbalance; (d) void; and (e) nonactive currents.

Another matter to highlight in Fig. 9 is the behavior of the APF's DC voltage control, which provides an adequate response, regardless of the current terms being processed. Such voltage remained within the upper and lower limits designed for the APF, considering a voltage ripple of 3% of the reference value, i.e. 500V. For instance, the DC bus presented maximum absolute variations of ΔV_I = 6.2 V, ΔV_{II} = 8.2 V, ΔV_{III} = 3.4 V and ΔV_{IV} = 9.2 V, respectively for cases I, II, III and IV. Such measurements are calculated based on the difference between the maximum and minimum voltage levels attained in Fig. 9 for each case. In general, based on a selective strategy, the results of the simulated scenarios restate that the CPT can be adequately employed to provide current quality improvement in *2Φ3w*

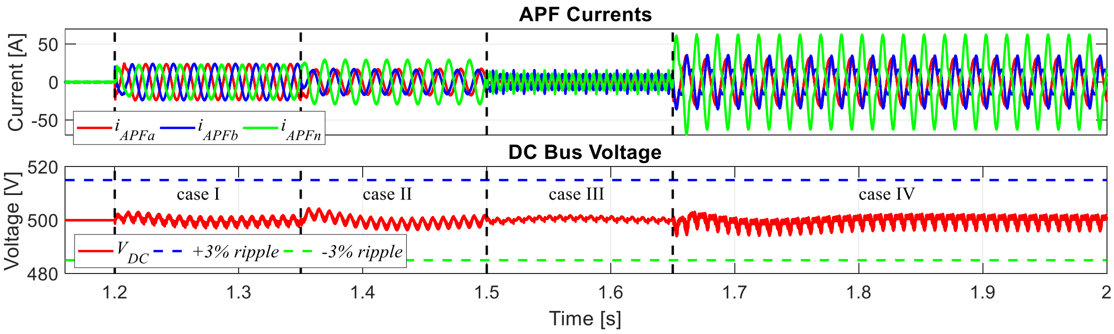

Fig. 9. APF currents and DC bus voltage for all simulated cases.

networks, mitigating harmonics and unbalance, as well as offering reactive compensation. Besides, several improvements can still be implemented using the presented methodology, e.g., considering dynamic saturation of converters [23], [20], in addition to the possibility to expand the functionality of injecting active power if considering the design of multifunctional distributed generators.

V. CONCLUSIONS

This work demonstrated that the Conservative Power Theory (CPT) can be adequately applied on the decomposition of current components and to control power conditioners in *2Φ3w* systems, providing current quality enhancement and increasing the flexibility of the system. As demonstrated by the simulation results, the proposed methodology can drive three-leg active power filters in a selective manner, offering selective compensation of reactive, unbalance and harmonic currents, as well as reducing the neutral current.

Further studies aim to evaluate the operation of the proposed method upon the consideration of unbalanced and distorted grid voltage conditions. Moreover, the application of such approach in *2Φ3w* grids shall be assessed concerning the existence of distributed generators comprised of multifunctional inverters, which would additionally extend operational possibilities to offer active current injection.

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