

A comprehensive proposition for lowering down the source-end in-phase currents using the APF-based devices

Abstract. The main goal of this paper is the proposition and analytical examination of successful neutral current cancellation methods. A generalized time-domain rule is suggested in order to achieve full cancellation of the source-end neutral current under unbalanced and distorted load-terminal voltage waveforms. The proposed rule makes it clear that any time-domain method have to observe the proposed technique in order to be capable of eliminating the neutral current under non-ideal load voltages. In this context, the IRP, the CMIP and the Z_GTIP methods, are reviewed as the well-known successful algorithms in cancelling the zero sequence current under non-ideal circumstances. While these methods appear to be dissimilar or unrelated, as another contribution of this paper, it is concluded that the aforementioned methods are derived from the same root that is obtained from a minimization problem. In the mean time, a comprehensive analytical performance assessment as well as the required modification is presented on these methods to show the precise reason of their efficiency under non-ideal load-terminal voltages. Further, simulations will make the significance of the proposed idea clear in cancelling the source-end neutral current.

Streszczenie. Głównym celem tego artykułu jest zaproponowanie i analityczne zbadanie skutecznych metod eliminacji prądu przewodu zerowego. Zaproponowano ogólną regułę w dziedzinie czasu, prowadzącą do pełnej redukcji prądu przewodu zerowego w przypadku niezrównoważonych i odkształconych przebiegów napięć na zaciskach źródła. Z zaproponowanej reguły jasno wynika, że jakkolwiek metoda w dziedzinie czasu, aby była w stanie zredukować prąd w przewodzie zerowym musi być zgodna z metodą proponowaną w tym artykule. W związku z tym, dokonano przeglądu metod IRP, CMIP i Z_GTIP ogólnie uznawanych za skuteczne w eliminacji prądu składowej zerowej w warunkach rzeczywistych. Jakkolwiek metody te wydają się być odmienne oraz wzajemnie niepowiązane, stwierdzono, że są one podobnie zakorzenione w problemie minimalizacyjnym. Aby pokazać szczegółowe przyczyny skuteczności tych metod w warunkach nieidealnego zasilania, w artykule przedstawiono analityczną ocenę ich skuteczności, a także potrzebę modyfikacji. Znaczenie proponowanej metody eliminacji prądu w przewodzie zerowym potwierdzone jest modelowaniem. **(Kompletna propozycja sposobu zmniejszania prądów za pomocą aktywnych filtrów mocy)**

Keywords: active power filter, neutral current, instantaneous powers, compensation.

Słowa kluczowe: aktywny filtr mocy, prąd przewodu zerowego, moce chwilowe, kompensacja

Introduction

Derivation of reference currents for the compensation is a critical step in the APF performance ([1]). Thus, any deficiency leads to malfunction of the device. Normally, APF reference current extraction methods work suitably under ideal load voltages. On the other hand, a number of these methods fail to achieve a satisfactory compensation result when the load voltages are unbalanced or non-sinusoidal. Proposing a generalized method to be capable of full cancellation of the source-end neutral current under non-ideal load voltages is desirable. To reach the mentioned target, an optimization problem is defined. Then, by solving this problem, a powerful neutral current cancelling method is suggested that is so straightforward. In addition, the instantaneous reactive power (IRP) [2], the complementary method of instantaneous powers (CMIP) [3] and the zero generalized theory of instantaneous powers (Z_GTIP) [4] methods as the instances capable in preserving their ability in full cancellation of source-end neutral current are analytically and mathematically assessed to reveal the relationship between them and the devised technique as well as to explain the precise reasons for their success.

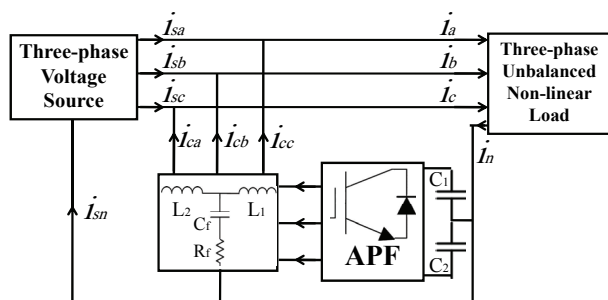


Fig. 1. A typical interconnection of the source, the load and the compensator across a three-phase four-wire power system

Furthermore, it is proved that some well-known methods are based on the same origin. Actually, even though they have dissimilar structures, they are different aspects of the

proposed idea in this paper with identical performance. Additionally, the possibility of employing the devised idea to improve the performance of the other time-domain compensation methods is investigated.

This paper proposes a generalized compensation method to cancel the source end neutral current. Then, the IRP, the CMIP and the Z_GTIP methods are reviewed in brief. Further, the relationship between these methods and the proposed generalized method is clarified and the significance of the provided idea in cancelling the source end neutral current is discussed. The simulation results are presented to verify the discussed procedures. Finally, the conclusions of this work are summarized.

The proposed generalized idea

Assume a three-phase load with the instantaneous voltages as $\mathbf{v}(t)=[v_a(t) \ v_b(t) \ v_c(t)]^t$ and the instantaneous currents as $\mathbf{i}(t)=[i_a(t) \ i_b(t) \ i_c(t)]^t$ (Fig. 1). An optimization problem is introduced to extract the desirable source currents ($\mathbf{i}_{ds}(t)$). The full cancellation of the source-end neutral current ($i_{sn}(t)$) should be fulfilled. Besides, the load instantaneous active power ($p(t)$) should be only delivered by $\mathbf{i}_{ds}(t)$. The optimization problem can be defined as:

$$\begin{aligned} & \text{Minimize } \sum_{k=a,b,c} (i_{dsk}(t))^2 \\ (1) \quad & \text{Subject to: } \mathbf{v}(t) \cdot (\mathbf{i}(t) - \mathbf{i}_{ds}(t)) = 0, \quad \sum_{k=a,b,c} (i_{dsk}(t)) = 0 \end{aligned}$$

Solving the problem by the well-known Lagrange multiplier method leads to:

$$(2) \quad \mathbf{i}_{ds}(t) = \frac{p(t)}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))} (\mathbf{v}(t) - \mathbf{v}^o(t))$$

where $\mathbf{v}^o(t) = (v_a(t) + v_b(t) + v_c(t))/3$ and $\mathbf{v}^o(t) = [v^o(t) \ v^o(t) \ v^o(t)]^t$ are the voltage zero sequence component and the voltage zero sequence component vector, respectively. By applying the compensation reference currents as $\mathbf{i}_c(t) = \mathbf{i}(t) - \mathbf{i}_{ds}(t)$, full cancellation of $i_{sn}(t)$ will be accomplished:

$$(3) \quad i_{sn}(t) = 3i_s^o(t) = \sum_{k=a,b,c} i_{dsk}(t) = 0$$

where $i_s^o(t)$ is the source-end zero sequence current.

It is easily provable that after compensation by almost all of the APF time-domain compensation methods the source currents ($i_s(t)$) could achieve the structure like below [2-14]:

$$(4) \quad \mathbf{i}_s(t) = \frac{(\text{power})}{(\text{voltage})(\text{voltage})}(\text{voltage})$$

where the *voltage* means a value that has the voltage dimension and the *power* is related to a value which has the power dimension. Actually, the methods with the configurations includable in (4) would necessarily involve the discussed idea (the zero sequence component exclusion from the load voltages in (4)) in order to have full cancellation of $i_{sn}(t)$ after compensation[2-10]. Otherwise, it would be impossible to maintain the source-end zero sequence current near zero [11-14].

The compensation techniques

Lots of the time-domain compensation methods could be noticed as the case studies for the above-expressed idea. However, it is not possible to cover all of them in a paper. In this section, the IRP, the CMIP and the Z_GTIP methods will be reviewed and then, their suggested compensation reference currents will be considered.

1. The IRP method

Assume $\mathbf{v}_{\alpha\beta o}(t)=[v_o(t) \ v_{\alpha}(t) \ v_{\beta}(t)]^t$ and $\mathbf{i}_{\alpha\beta o}(t)=[i_o(t) \ i_{\alpha}(t) \ i_{\beta}(t)]^t$ as the load voltages and currents respectively. Instantaneous powers could be defined as below ([2], [5]):

$$(5) \quad \begin{cases} p(t) = p_{\alpha\beta}(t) + p_o(t), p_o(t) = v_o(t) i_o(t) \\ p_{\alpha\beta}(t) = v_{\alpha}(t) i_{\alpha}(t) + v_{\beta}(t) i_{\beta}(t) \\ q_{\alpha\beta}(t) = v_{\alpha}(t) i_{\beta}(t) - v_{\beta}(t) i_{\alpha}(t) \end{cases}$$

where $p_{\alpha\beta}(t)$, $q_{\alpha\beta}(t)$ and $p_o(t)$ are the instantaneous active (real) power, the instantaneous reactive (imaginary) power and the instantaneous O direction power, respectively. Compensation reference current $\mathbf{i}_{c\alpha\beta o}(t)=[i_{co}(t) \ i_{c\alpha}(t) \ i_{c\beta}(t)]^t$ can be extracted as ([5]):

$$(6) \quad \begin{aligned} i_{co}(t) &= i_o(t) \\ \begin{bmatrix} i_{c\alpha}(t) \\ i_{c\beta}(t) \end{bmatrix} &= \frac{1}{v_{\alpha}^2(t) + v_{\beta}^2(t)} \begin{bmatrix} v_{\alpha}(t) & -v_{\beta}(t) \\ v_{\beta}(t) & v_{\alpha}(t) \end{bmatrix} \\ &\quad \times \begin{bmatrix} \tilde{p}_{\alpha\beta}(t) - \bar{p}_o(t) \\ q_{\alpha\beta}(t) \end{bmatrix} \end{aligned}$$

where $\bar{p}_o(t)$ and $p_{\square\alpha\beta}(t)$ are the average part of $p_o(t)$ and the oscillating part of $p_{\alpha\beta}(t)$, respectively.

2. The CMIP method

It has been shown in [4] that in a three phase system with no zero sequence voltage or current, if the source is urged to deliver the following currents, compensation of the (instantaneous) reactive power $\mathbf{q}(t)=\mathbf{v}(t)\times\mathbf{i}(t)$ (defined in [11]) would be accomplished:

$$(7) \quad \mathbf{i}_B(t) = \begin{bmatrix} i_{Ba}(t) \\ i_{Bb}(t) \\ i_{Bc}(t) \end{bmatrix} = \begin{bmatrix} i_a(t) + i_b(t) \frac{v_a(t)}{v_b(t)} + i_c(t) \frac{v_a(t)}{v_c(t)} \\ i_a(t) \frac{v_b(t)}{v_a(t)} + i_b(t) + i_c(t) \frac{v_b(t)}{v_c(t)} \\ i_a(t) \frac{v_c(t)}{v_a(t)} + i_b(t) \frac{v_c(t)}{v_b(t)} + i_c(t) \end{bmatrix}$$

Assume $p_B(t)$ is the instantaneous active power which is generated due to $\mathbf{i}_B(t)$. Then, the following relation can be derived:

$$(8) \quad \begin{cases} p_B(t) = v_a(t) i_{Ba}(t) + v_b(t) i_{Bb}(t) + v_c(t) i_{Bc}(t) \\ p(t) = v_a(t) i_a(t) + v_b(t) i_b(t) + v_c(t) i_c(t) \end{cases}$$

In a real compensated system, $p(t)$ and $p_B(t)$ should be identical. Therefore, the coefficient $\gamma(t)$ is defined as:

$$(9) \quad \gamma(t) = p_B(t) / p(t)$$

Thus, the source current ($i_s(t)$) and the compensator current ($i_c(t)$) can be expressed as:

$$(10) \quad \mathbf{i}_s(t) = (1/\gamma(t))\mathbf{i}_B(t) \quad , \quad \mathbf{i}_c(t) = \mathbf{i}(t) - \mathbf{i}_s(t)$$

By applying (10), however, full cancellation of $i_{sn}(t)$ cannot be achieved under non-ideal load voltages. The zero sequence voltage inactive power (*voIP*) and the zero sequence current inactive power (*ioIP*) have been introduced as the deficiency reasons. Both of *voIP* and *ioIP* have indicated portions of the load inactive power which are supplied by the source. In order to remedy the described compensation weakness, it has been proposed in [4] to compensate the load inactive power $\mathbf{q}'(t)$ instead of $\mathbf{q}(t)$ where the former can be derived as:

$$(11) \quad \mathbf{q}'(t) = \mathbf{q}(t) - (\text{voIP} - \text{ioIP})$$

It should be mentoned that proposing $\mathbf{i}_B(t)$ as (7) is just for elaborating the method and its implementation is not exactly in the same manner.

3. The Z_GTIP method

It has been proposed in [4] to use (12) as $\mathbf{i}_c(t)$:

$$(12) \quad \begin{aligned} \mathbf{i}_c(t) &= [\tilde{p}(t) - 3p^o(t)] \frac{(\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))} \\ &\quad + \frac{[(\mathbf{v}(t) - \mathbf{v}^o(t)) \times \mathbf{i}(t)] \times (\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))} \end{aligned}$$

where $p^o(t)=v^o(t)^2(t)$ is the zero sequence instantaneous power and $p_{\square}(t)$ is the oscillating part of $p(t)$.

Clarification of relationships

1. The relationship between the IRP and the proposed methods

Let us define $\mathbf{v}_{\alpha\beta}(t)$ as $\mathbf{v}_{\alpha\beta}(t) \square [0 \ v_{\alpha}(t) \ v_{\beta}(t)]^t$.

Employing $\mathbf{v}_{\alpha\beta}(t)$, (6) can be reshaped as below:

$$(13) \quad \begin{aligned} \mathbf{i}_{c\alpha\beta o}(t) &= \frac{\tilde{p}_{\alpha\beta}(t) - \bar{p}_o(t)}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)} \mathbf{v}_{\alpha\beta}(t) \\ &\quad + \frac{1}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)} \begin{bmatrix} (v_{\alpha}^2(t) + v_{\beta}^2(t)) i_o(t) \\ -v_{\beta}(t) q_{\alpha\beta}(t) \\ v_{\alpha}(t) q_{\alpha\beta}(t) \end{bmatrix} \end{aligned}$$

Uncomplicatedly, (13) could be altered as:

$$(14) \quad \begin{aligned} \mathbf{i}_{c\alpha\beta o}(t) &= \frac{p_{\alpha\beta}(t) - \bar{p}(t)}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)} \mathbf{v}_{\alpha\beta}(t) + \frac{(\mathbf{v}_{\alpha\beta}(t) \times \mathbf{i}_{\alpha\beta o}(t)) \times \mathbf{v}_{\alpha\beta}(t)}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)} \\ &= \frac{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{i}_{\alpha\beta o}(t) - \bar{p}(t)}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)} \mathbf{v}_{\alpha\beta}(t) \end{aligned}$$

$$+ \frac{(\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)) \mathbf{i}_{\alpha\beta o}(t) - (\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{i}_{\alpha\beta o}(t)) \mathbf{v}_{\alpha\beta}(t)}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)}$$

$$\rightarrow \mathbf{i}_{C_{\alpha\beta o}}(t) = \mathbf{i}_{\alpha\beta o}(t) - \frac{\bar{p}(t)}{\mathbf{v}_{\alpha\beta}(t) \cdot \mathbf{v}_{\alpha\beta}(t)} \mathbf{v}_{\alpha\beta}(t)$$

Accordingly, (14) can be modified as:

$$(15) \quad \mathbf{i}_c(t) = \mathbf{C}^{-1} \mathbf{i}_{C_{\alpha\beta o}}(t)$$

$$= \mathbf{i}(t) - \frac{\bar{p}(t)}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))} (\mathbf{v}(t) - \mathbf{v}^o(t))$$

Interestingly, comparing (15) with (2), it is obvious that compensation reference currents of the IRP and the proposed methods are analogues and, accordingly, satisfactory cancellation of $i_{sn}(t)$ can be achieved by applying both of them.

2. The relationship between the CMIP and the proposed methods

Equations (7) and (8) could be rewritten as:

$$(16) \quad \mathbf{i}_B(t) = \eta(t) \mathbf{v}(t)$$

$$(17) \quad p_B(t) = \mathbf{v}(t) \cdot \mathbf{i}_B(t) = \eta(t) [\mathbf{v}(t) \cdot \mathbf{v}(t)]$$

where $\eta(t) = (i_a(t)/v_a(t) + i_b(t)/v_b(t) + i_c(t)/v_c(t))$. By substituting (16) and (17) into (10), the following relation could be obtained:

$$(18) \quad \mathbf{i}_s(t) = \frac{1}{\gamma(t)} \mathbf{i}_B(t) = \frac{p(t)}{\mathbf{v}(t) \cdot \mathbf{i}_B(t)} \mathbf{i}_B(t)$$

$$= \frac{p(t)}{\mathbf{v}(t) \cdot \mathbf{v}(t)} \mathbf{v}(t) = \mathbf{i}_p(t)$$

$i_p(t)$ is the instantaneous active current defined by the GTIP method [6]. Thus, (18) makes it clear that, under ideal load voltages, structures and performance of the CMIP and the GTIP methods are identical. It is noticeable that the GTIP method performs compensation by employing the average part of $p(t)$ ($\bar{p}(t)$) in its process. In the case of the zero sequence component attendance in the load voltages, the following relations can be extracted by applying (11) in (7) and (8):

$$(19) \quad \begin{cases} \mathbf{i}_B(t) = \lambda(t) [\mathbf{v}(t) - \mathbf{v}^o(t)] \\ \lambda(t) = \left(\frac{i_a(t)}{v_a(t) - v^o(t)} + \frac{i_b(t)}{v_b(t) - v^o(t)} + \frac{i_c(t)}{v_c(t) - v^o(t)} \right) \end{cases}$$

$$(20) \quad p_B(t) = \lambda(t) (\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))$$

Applying the above relations, (18) could be changed to:

$$(21) \quad \mathbf{i}_s(t) = \frac{p(t) \lambda(t) (\mathbf{v}(t) - \mathbf{v}^o(t))}{\lambda(t) (\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$= \frac{p(t)}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))} (\mathbf{v}(t) - \mathbf{v}^o(t))$$

A comparison between (2) and (21) would indicate that the compensation reference currents in the proposed and the CMIP methods are exactly the same. The mentioned fact implies the exact reason of similarity in full cancellation of $i_{sn}(t)$ by applying both of them.

3. The relationship between the Z_GTIP and the proposed methods

Employing the vector product and linear algebra rules, it is provable from (12) that $i_s(t)$ after applying the Z_GTIP method becomes as follow:

$$(22) \quad \mathbf{i}_c(t) = [\tilde{p}(t) - 3p^o(t)] \frac{(\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$+ \frac{[(\mathbf{v}(t) - \mathbf{v}^o(t)) \times \mathbf{i}(t)] \times (\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$= [p(t) - 3p^o(t) - \bar{p}(t)] \frac{(\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$+ \frac{[(\mathbf{v}(t) - \mathbf{v}^o(t)) \times \mathbf{i}(t)] \times (\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$= [(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot \mathbf{i}(t) - \bar{p}(t)] \frac{(\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$+ \frac{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t)) \mathbf{i}(t)}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$- \frac{[(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot \mathbf{i}(t)] (\mathbf{v}(t) - \mathbf{v}^o(t))}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))}$$

$$= \mathbf{i}(t) - \frac{\bar{p}(t)}{(\mathbf{v}(t) - \mathbf{v}^o(t)) \cdot (\mathbf{v}(t) - \mathbf{v}^o(t))} (\mathbf{v}(t) - \mathbf{v}^o(t))$$

By comparing (2) with (22), the analogues capability of full cancellation of $i_{sn}(t)$ between the Z_GTIP and the proposed methods can be revealed.

According to the mentioned analysis and expressions, $\mathbf{v}^o(t)$ is excluded from the load voltages used in the reference extraction process. One could examine the possibility to employ this idea to improve the performance of those time-domain compensation methods which are identical to (4) and have deficiencies in cancelling the source end neutral current. This makes the aforementioned compensation methods capable in full cancellation of $i_{sn}(t)$.

Simulations

An unbalanced non-linear load (as can be seen in Fig. 1) consisted of three single-phase diode rectifiers is compensated under two different cases namely case 1: the ideal load voltages with an rms value of 200V-50Hz and case 2: the non-ideal load voltages as follow:

$$(23) \quad \begin{cases} v_a(t) = 70\sqrt{2} \sin(\omega t) + 10 \sin(3\omega t - 18^\circ) \\ v_b(t) = 170\sqrt{2} \sin(\omega t - 100^\circ) + 20 \sin(3\omega t - 90^\circ) \\ v_c(t) = 220\sqrt{2} \sin(\omega t + 130^\circ) + 10 \sin(3\omega t - 26^\circ) \end{cases}$$

The non-linear load consists of three single-phase rectifiers that feed the following circuit elements:

$$(24) \quad \begin{cases} R_a = 6\Omega, L_a = 1\text{mH}, C_a = 0.3\text{mF} \\ R_b = 4\Omega, L_b = 1\text{mH}, C_b = 0.2\text{mF} \\ R_c = 6\Omega, L_c = 1\text{mH}, C_c = 0.2\text{mF} \end{cases}$$

The active filter, like the compensator, includes an AC/DC converter with three arms together with the fourth wire that is connected to the mid-point of the two capacitive DC links. Two capacitor voltages are controlled using a PI controller. A hysteresis current control modulation technique is employed that drives the switches with variable frequencies [15]. A passive LCL-filter is used to attenuate the unwanted frequency components resulting

from the switching modulation [16]. Parameters of the converter and the LCL-filter are tabulated in Table 1.

Table 1. The parameters of the compensating active power filter

APF side LCL filter inductance L_1	4.1 [mH]
Grid side LCL filter inductance L_2	0.4 [mH]
LCL filter capacitor C_f	10 [μ F]
LCL filter damping resistor R_f	20 [Ω]
APF Switching frequency	6 : 9 [kHz]
APF DC-link capacitors (each one)	2 [mF]
APF DC-link voltage	700 [V]

The following simulations are arranged in order to discuss the practical issues.

1. Case 1: Balanced and sinusoidal load voltages

Figures 2(a)-(b) show the load-terminal voltages and the non-linear load currents, respectively.

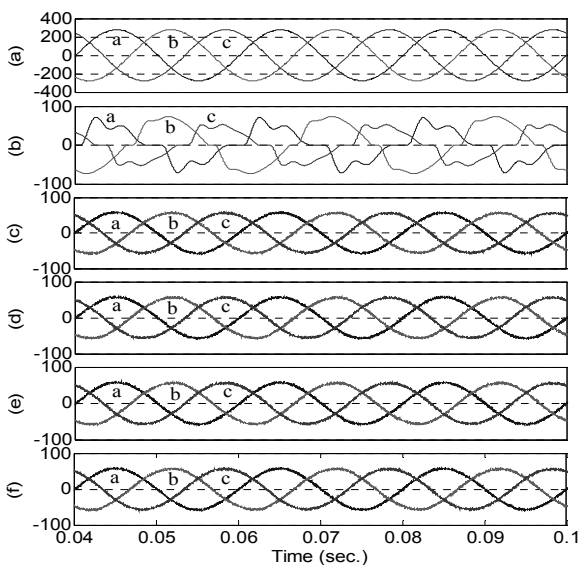


Fig. 2. a) three phase balanced load voltages (V) b) asymmetrical distorted load currents (A), three-phase source currents (A) after compensation with c) the GTIP d) the IRP e) the Z_GTIP and f) the proposed methods.

Also, Fig. 3(a) introduces the big magnitude current of the neutral-wire of the non-linear load. Figures 2(c)-(f) illustrate the source currents after performing the compensation by the GTIP, the IRP, the Z_GTIP and the proposed compensation methods respectively. It can be seen that the rules cancel successfully the load unbalance. The source-end neutral-wire current is illustrated by Fig. 3(b)-(e), which is canceled as expected. It is noticeable that the load-terminal voltages cannot be assumed balanced and sinusoidal under non-linear load because of the nonzero source internal impedance.

2. Case 2: Unbalanced and distorted load voltages

Note that unbalance and distortion of (23) are exaggerated in order to achieve a better comparison on the performance of different compensation rules. Figure 4(a) show non-ideal load-terminal voltages stated by (23), Fig. 4(b) depicts the non-linear load currents and Fig. 5(a) the neutral current of the load.

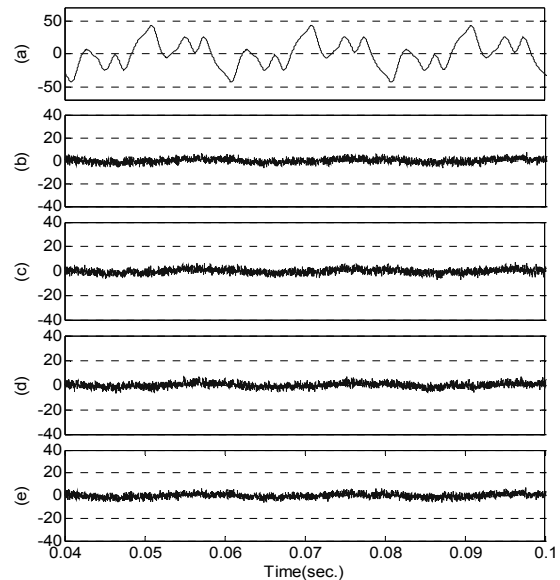


Fig. 3. a) the load-end neutral current (A), the source-end neutral current (A) after compensation with b) the GTIP c) the IRP d) the Z_GTIP and e) the proposed methods.

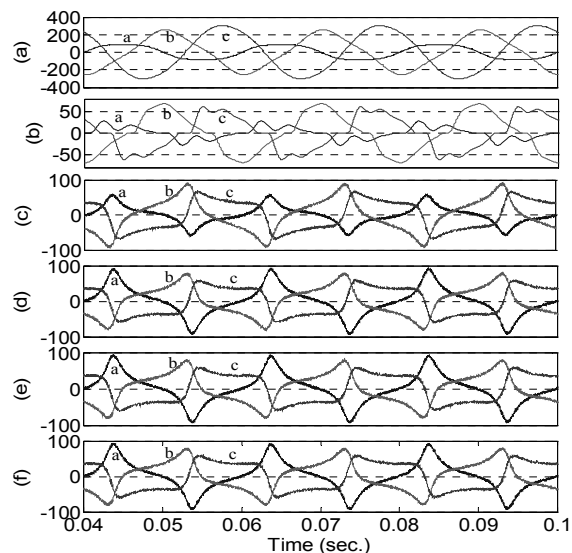


Fig. 4. a) three phase asymmetrical load voltages (V) b) asymmetrical distorted load currents (A), three-phase source currents (A) after compensation with c) the GTIP d) the IRP e) the Z_GTIP and f) the proposed methods.

Figures 2(c)-(f) illustrate the source currents after performing the compensation by the GTIP, the IRP, the Z_GTIP and the proposed compensation methods respectively. The source-end neutral-wire current is shown by Fig. 5(b)-(e). It is obvious that the GTIP is unable to cancel the source-end neutral current under unbalanced load voltages as shown by Fig. 5(b), worsening unbalance of the source currents. On the other hand, the IRP, the Z_GTIP and the proposed methods, as it has been previously clarified, could preserve their capability in cancelling the source-end zero-sequence current even under non-ideal load voltages.

Although by applying the abovementioned methods the source side neutral current can be fully cancelled under non-ideal load voltages, distortion of the source current is not improved because the negative sequence voltage of the load-terminal remains uncompensated.

The rms-amount of source-end neutral currents is presented in Table 2.

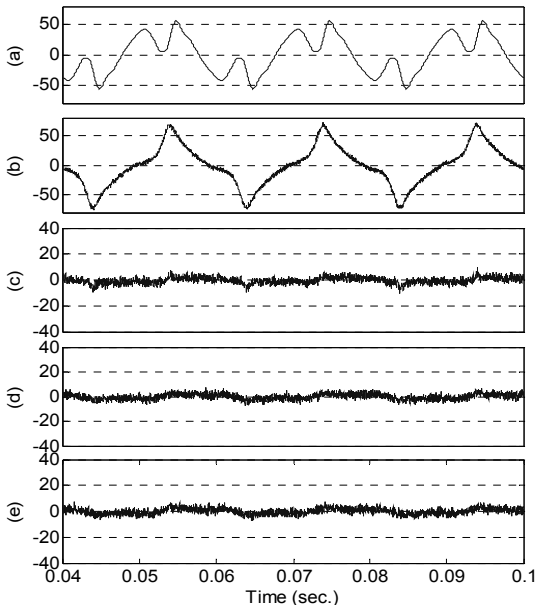


Fig. 5. a) the load-end neutral current (A), the source-end neutral current (A) after compensation with b) the GTIP c) the IRP d) the Z_GTIP and e) the proposed methods.

It is again worthy to mention that this paper has been proposed with the aim of the source-end neutral current cancellation under the distorted and unbalanced load voltages. Therefore, the harmonic and reactive power perfect compensations are not involved in. However, it could be accomplished by including the suggestions recommended in [6].

Table 2. Source-end rms neutral current after employing various compensating methods (A)

	Case 1	Case 2
Uncompensated	20.3	30.97
GTIP	2.11	33.71
IRP	2.12	2.51
CMIP	2.12	2.46
Z_GTIP	2.11	2.48
The Proposed Method	2.11	2.46

Conclusions

This paper concentrates on the APF-based zero sequence components and proposes a method for the source-end neutral current cancellation under non-ideal load voltages. A generalized time-domain method is introduced that is capable of full cancellation of the source-end neutral current under unbalanced and distorted load voltage waveforms. Further, it is shown that the presence of the zero sequence component on the load voltages is the reason for malfunctioning of a number of time-domain compensation methods such as the GTIP. Thus, in brief, it is essential to exclude the zero sequence voltage in order to have full cancellation of the source-end zero sequence current. Analytically, the compensation performance of the IRP, the CMIP and the Z_GTIP methods, as the successful instances in full cancellation of the source-end neutral current, are investigated and their relationships are thoroughly clarified. Moreover, it is proved that although the considered techniques are apparently dissimilar, they can be related pretty the same to a minimized solution. Actually, they are different derivation out of the proposed method in this paper with an identical performance.

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