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Comparison and classification of six reference currents extraction algorithms for harmonic compensation on a stochastic power network: Case of the TLC hybrid filter

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Abstract: This article highlights a comparison and classification of six algorithms for extracting reference currents used in the context of harmonic compensation for the case of a TLC hybrid filter on a stochastic electrical network. With the ultimate goal of determining the most robust and reliable algorithm, the electrical network presents four variable configurations such as, operation in sinusoidal and balanced voltage, sinusoidal and unbalanced voltage, balanced and disturbed voltage, or even in unbalanced voltage and disrupts. Firstly, a presentation of these six algorithms or methods identified in the time domain will be made with injections of the fifth-order harmonics taken in positive sequences during the execution or compilation of the six algorithms for the four network operating hypotheses. And in a

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PUBLIC INTEREST STATEMENT

The quality of electrical energy is positioned as a determining factor in the industrial, economic, and social development of several countries in the world and in this case in the case of Cameroon and Chad. This is why the optimization of harmonic depollution on a stochastic three-phase electrical network occupies an important place in this article. It is therefore a question of comparing the performance of several algorithms for extracting reference currents under complex conditions and very close to the industrial world (by associating external and varied disturbances) during depollution or harmonic compensation processes, all combined with a hybrid filter. For the sole purpose of optimizing online harmonic depollution by choosing and implementing the most suitable algorithm according to the characteristics of the electrical network in force at the end of the study, the results obtained in this work will contribute to increasing the lifespan and production capacities of electrical systems in general and especially in the industrial sector.
second step, a cross-comparison of the performances on the basis of indicators such as the THD (harmonic distortion rate) and UFI (unbalance factors) required by the IEEE 519–2014 and EN 50160 standard, then a cross-validation is based on some results available in the literature. These results will now facilitate the choice of the most appropriate algorithm depending on the nature of the electrical network in force according to the case studies.

Subjects: Engineering Management; Power & Energy; Systems & Control Engineering

Keywords: current extraction algorithms; nature of the electricity network; THD; classification; TLC hybrid filter

1. Introduction

The proliferation of non-linear loads is growing exponentially with technological evolution. In general, energy electronics receive special attention for several researchers and engineers at the level of harmonic contamination for harmonic power systems, which are at the origin of the degradation of the power factor, the overheating and the complete destruction of equipment, the errors in the measurements with the instruments, the breakdown of the capacitors (Akagi et al., 1999). In order to reduce the harmonic currents, the standard IEEE 519 – 2014 was adopted. The overall harmonic distortion must be at most 5% of the initial value before filtering (Kim & Akagi, 1999). Therefore, the current 5% THD limit has always been the performance target that all researchers and designers do their best to achieve. In order to deal directly with harmonic problems and to respect the 5% limits, conventional passive harmonic filters are applied. However, due to their major weaknesses of bulky sizes and patch mitigation tools, innovative harmonic mitigation tools and efficient hybrid filters, combining passive and active models are being developed to replace them. In addition, the development of hybrid filters is also being spurred by the emergence of power semiconductor switching devices such as insulated gate bipolar transistors (IGBTs), thyristor and the availability of powerful controllers such as processors and digital signals (DSP; Shu et al., 2022). On the other hand, the success of the compensation or filtering process depends on the reliability and robustness of the algorithm for extracting the reference currents while knowing that the current control laws that cannot act correctly when the network is disturbed and unbalanced in tension. Based on this observation, the aim of this work is to provide a solution to this problem by the comparative evaluation of the techniques for extracting the reference currents. This paper presents the review of six control strategies (original p-q, modified p-q, p-q pseudo mapping matrix, par, NFp-q and DCAP methods) for operating conditions in sinusoidal and balanced voltage, sinusoidal and unbalanced voltage, voltage balanced and disturbed, or in unbalanced and disturbed tensions, with the ultimate goal of determining the most suitable method in the event of disturbances.

Figure 1. Functional diagram to extract the reference current based on the original p-q method (Harrison).
2. Reference current extraction algorithms

2.1. The P-Q method ON A 4-wire network

The original p-q theory is defined by a transformation of the electrical quantities of coordinates a, b, c into coordinates α, β, 0. A homogeneity exists between the powers expressed in the two coordinates. This method is based on the notion of instantaneous active power \( P(t) \) and reactive power \( q(t) \), which is the originality of the method (Marini et al., 2019) as shown in figure 1.

\[
\begin{align*}
\{ v_a(t) + v_b(t) + v_c(t) &= v_n \\
i_a(t) + i_b(t) + i_c(t) &= i_n
\}
\tag{1}
\end{align*}
\]

With \( v_n(t) = 3v_0(t) \) and \( i_n(t) = 3i_0(t) \), the neutral unbalance voltage and current in the reference \( a, b, c \), \( v_0(t) \) and \( i_0(t) \) are the homopolar in the coordinates \( a, b, c \). The zero sequence voltage and the current in the coordinates \( α, β, 0 \) are given by:

\[
\begin{align*}
v_0(t) &= \frac{v_α}{\sqrt{3}} \\
i_n(t) &= \frac{i_α}{\sqrt{3}}
\end{align*}
\tag{2}
\]

The transformation in the orthogonal coordinate system \( α, β, 0 \) of the current of a three-phase system are

\[
\begin{bmatrix}
i_0 \\
i_α \\
i_β
\end{bmatrix} = C_{33}
\begin{bmatrix}
i_0 \\
i_α \\
i_β
\end{bmatrix}
\tag{3}
\]

In addition, the tension is:

\[
\begin{bmatrix}
v_0 \\
v_α \\
v_β
\end{bmatrix} = C_{33}
\begin{bmatrix}
v_0 \\
v_α \\
v_β
\end{bmatrix}
\tag{4}
\]

With \( C_{33} \) is the Concordia transformation matrix defined by:

\[
C_{33} = \sqrt{\frac{2}{3}}
\begin{bmatrix}
\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}}
\end{bmatrix}
\tag{5}
\]

In this theory for a four-wire application, we consider that the zero sequence circuit is independent of the circuit in the coordinate, we define two active powers \( P0 \) and \( Paβ \) in addition to reactive power \( qαβ \). The total instantaneous active power is defined as the sum of the two active powers and the instantaneous reactive power is the same for the 3-wire p-q system (“IEEE Recommended Practice and Requirements,” 2014; Mistry & Patel, 2017; Shu et al., 2022)

\[
P(t) = P_0 + P_{αβ} = P_0 + v_αi_α + v_βi_β = v_αi_α + v_βi_β + v_0i_n
\tag{6}
\]

\[
q(t) = q_{αβ} = v_αi_β - v_βi_α
\tag{7}
\]

Or,
\[
\begin{aligned}
& P_{qref} = P_{qref} + P_{qref} \\
& q_{qref} = q_{qref} + q_{qref}
\end{aligned}
\]  
(8)

The powers in the reference \( \alpha, \beta, 0 \) are expressed as below:

\[
\begin{bmatrix}
P_{qref} \\
q_{qref}
\end{bmatrix} =
\begin{bmatrix}
v_0 & 0 & 0 \\
0 & v_\alpha & v_\beta \\
0 & -v_\beta & v_\alpha
\end{bmatrix}
\begin{bmatrix}
i_0 \\
i_\alpha \\
i_\beta
\end{bmatrix}
\]  
(9)

Currents in the system \( \alpha, \beta, 0 \) are given as

\[
\begin{bmatrix}
i_0 \\
i_\alpha \\
i_\beta
\end{bmatrix} = \frac{1}{v_0 v_{qref}}
\begin{bmatrix}
v_{qref} & 0 & 0 \\
0 & v_0 v_\alpha & -v_0 v_\beta \\
0 & v_0 v_\beta & v_0 v_\alpha
\end{bmatrix}
\begin{bmatrix}
P_0 \\
P_{qref} \\
q_{qref}
\end{bmatrix}
\]  
(10)

\[
v_{qref}^2 = v_0^2 + v_{qref}^2
\]  
(11)

The reference currents as a function of the powers to be compensated are expressed as follows:

\[
\begin{bmatrix}
i_0 \\
i_\alpha \\
i_\beta
\end{bmatrix} = \frac{1}{v_0 v_{qref}}
\begin{bmatrix}
v_{qref} & 0 & 0 \\
0 & v_0 v_\alpha & -v_0 v_\beta \\
0 & v_0 v_\beta & v_0 v_\alpha
\end{bmatrix}
\begin{bmatrix}
P_0 \\
P_{qref} \\
q_{qref}
\end{bmatrix}
\]  
(12)

Once the reference currents in the coordinate \( \alpha, \beta, 0 \), are calculated, the inverse formulation of the matrix by Clark/Concordia \( C_{33}^{-1} \) gives these currents in the coordinates \( a, b, c \), according to the following relation (Hanna Nohra et al., 2019):

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} = C_{33}^{-1}
\begin{bmatrix}
i_0 \\
i_\alpha \\
i_\beta
\end{bmatrix}
\]  
(13)

\[
C_{33}^{-1} = \sqrt{\frac{2}{3}}
\begin{bmatrix}
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \sqrt{3} \\
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2}
\end{bmatrix}
\]  
(14)

2.2. Modified P-Q method on the 4-wire network

This technique explores the Concordia transformation applied to simple source voltage and line currents in order to obtain real, imaginary, and zero sequence instantaneous powers (Dubey et al., 2021; Sun et al., 2020; Yu & Tao, 2016). The direct component must be eliminated by transforming the fundamental component into a direct component and the harmonic component into oscillatory harmonics (Marini et al., 2019; Naderipour et al., 2018; Shu et al., 2022). This principle is as follows: consider simple voltage \( v_a(t), v_b(t), v_c(t) \) and line currents \( i_a(t), i_b(t), i_c(t) \) of a three-phase homopolar system. Each block of the current extraction diagram contains an equation as shown in figure 2. The Concordia transformation makes it possible to bring a three-phase system from \( a, b, c \) to \( \alpha, \beta, 0 \) coordinated as follows:
From there, we get the real, imaginary, and homopolar powers:

\[
\begin{bmatrix}
p_a \\
q_b \\
p_0
\end{bmatrix} = \begin{bmatrix}
v_a & v_p & 0 \\
v_p & v_a & 0 \\
0 & 0 & v_0
\end{bmatrix} \begin{bmatrix}
i_a \\
i_p \\
i_0
\end{bmatrix}
\]

(17)

These powers can be expressed as the sum of the direct components and the ripple component as follows:

\[
\begin{cases}
p = p + \bar{p} \\
q = q + \bar{q} \\
p_0 = p_0 + \bar{p}_0
\end{cases}
\]

(18)

The load current in the axes α, β, 0:

\[
\begin{bmatrix}
i_a \\
i_p \\
i_0
\end{bmatrix} = \frac{1}{v_0(v_a^2 + v_p^2)} \begin{bmatrix}
v_a v_0 & v_p v_0 & 0 \\
v_p v_0 & v_a v_0 & 0 \\
0 & 0 & (v_a^2 + v_p^2)
\end{bmatrix} \begin{bmatrix}
p \\
q \\
p_0
\end{bmatrix}
\]

(19)

With

\[v_a = \sqrt{3} \sin \theta \text{ and } v_p = -\sqrt{3} \cos \theta\]

(20)

Using 2.30, we get the expression of real and imaginary powers:

\[
\begin{bmatrix}
p \\
q
\end{bmatrix} = \begin{bmatrix}
v_a & v_p \\
-v_p & v_a
\end{bmatrix} \begin{bmatrix}
i_a \\
i_p
\end{bmatrix}
\]

(21)
The expression of the current in the plane $\alpha$, $\beta$, 0 as a function of the instantaneous power is given by:

$$
\begin{bmatrix}
  i_a \\
  i_p \\
  i_0
\end{bmatrix} = \frac{1}{v_0(v_a^2 + v_p^2)}
\begin{bmatrix}
  v_a & v_p & u_p \\
  -v_p & v_a & u_a \\
  v_p & v_a & 0
\end{bmatrix}
\begin{bmatrix}
  p \\
  q \\
  0
\end{bmatrix}
$$

Likely equation II.31, equation II.32 becomes

$$
\begin{bmatrix}
  i_a \\
  i_p \\
  i_0
\end{bmatrix} = \frac{1}{v_0(v_a^2 + v_p^2)}
\begin{bmatrix}
  v_a & -v_p & 0 \\
  v_p & v_a & 0 \\
  0 & 0 & (v_a^2 + v_p^2)
\end{bmatrix}
\begin{bmatrix}
  p \\
  q \\
  0
\end{bmatrix}
$$

Depending on the function given to the filter, it is possible to compensate the harmonic current and the reactive power or either the harmonic current or the reactive power (Abolfathi et al., 2017; Bhople & Rayarao, 2018; Chang et al., 2006; Hoon et al., 2017; Mistry & Patel, 2017).

We want to compensate for both at the same time, equation II.23 becomes:

$$
\begin{bmatrix}
  i_a \\
  i_p \\
  i_0
\end{bmatrix} = \frac{1}{v_0(v_a^2 + v_p^2)}
\begin{bmatrix}
  v_a & -v_p & 0 \\
  v_p & v_a & 0 \\
  0 & 0 & (v_a^2 + v_p^2)
\end{bmatrix}
\begin{bmatrix}
  \tilde{p} \\
  \tilde{q} \\
  0
\end{bmatrix}
$$

Finally, the reference current is obtained using the inverse Concordia transformation.

$$
\begin{bmatrix}
  i_{ra} \\
  i_{rb} \\
  i_{rc}
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
  \frac{1}{3} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
  -\frac{1}{3} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
  0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
  i_a \\
  i_p \\
  i_0
\end{bmatrix}
$$

### 2.3. P-Q pseudo-mapping matrix method

The modified p-q method could not compensate for the neutral current because the expression of the zero sequence reference component is not equal to the zero sequence current of the circuit. Then, the author proposes to modify the matrix so that the zero sequence currents and that of the power circuit are equal. This led to the pseudo-mapping matrix method. Powers are defined in the same way and the concept remains defined (Chicco et al., 2009; Hernández et al., 2011; Li et al., 2020; Santos et al., 2020; Suresh et al., 2011) as shown in figure 3.

![Figure 3. Functional diagram for extracting the reference current based on the p-q pseudo-mapping matrix method (Kalair et al., 2017).](image-url)
\[
\begin{bmatrix}
    i_0 \\
    i_{a} \\
    i_{b}
\end{bmatrix} = \begin{bmatrix}
    \frac{v_a}{\sqrt{3}} & 0 & \frac{v_b}{\sqrt{3}} & 0 \\
    \frac{v_a}{\sqrt{3}} & \frac{v_b}{\sqrt{3}} & \frac{v_c}{\sqrt{3}} & 0 \\
    \frac{v_a}{\sqrt{3}} & \frac{v_b}{\sqrt{3}} & 0 & \frac{v_c}{\sqrt{3}}
\end{bmatrix}
\begin{bmatrix}
    p - P_f \\
    q_0 \\
    q_a \\
\end{bmatrix}
\] (26)

The diagram in figure II.3 shows the extraction of the reference currents, which only changes at the level of equation (II.25) instead of (II.26).

2.4. The P-Q-R method

This method introduced by Kim performs a double transformation, a first transformation of the phase-to-neutral voltage and line currents of the coordinate a, b, c to the coordinate α, 0, then a second transformation of the coordinate α, 0 to coordinate PQR as shown in figure 4. Its principle is stated as follows: Consider simple voltage \(v_a(t), v_b(t), v_c(t)\) and charging currents \(i_a(t), i_b(t), i_c(t)\) of a three-phase homopolar system (Al-Mawali et al., 2011; Andari & Beheshti, 2011; Barutçu et al., 2019; De Araujo et al., 2021; Edri et al., 2021; Oliveira et al., 2018). The figure below illustrates the identification of the reference currents during harmonic current and reactive power compensation. The equations to be introduced in each block are collected as data as follows:

Using the Concordia transformation, we get the two relations as follows:

\[
\begin{bmatrix}
    v_a \\
    v_b \\
    v_0
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
    1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
    0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
    1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
    v_a \\
    v_b \\
    v_c
\end{bmatrix}
\] (27)

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_0
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
    1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
    0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
    1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix}
\] (28)

**Figure 4.** Functional diagram to extract the reference current based on the method p-q-r (Hanna Nohra et al., 2019).
The following transformation called p-q-r we give:

\[
\begin{bmatrix}
    i_p \\
    i_q \\
    i_r
\end{bmatrix} = \begin{bmatrix}
    \frac{v_x}{v_{0p}} & \frac{v_y}{v_{0p}} & \frac{v_z}{v_{0p}} \\
    -\frac{v_x}{v_{0q}} & \frac{v_y}{v_{0q}} & \frac{v_z}{v_{0q}} \\
    \frac{v_x}{v_{0r}} & -\frac{v_y}{v_{0r}} & \frac{v_z}{v_{0r}}
\end{bmatrix} \begin{bmatrix}
    i_p \\
    i_q \\
    i_r
\end{bmatrix}
\]

(29)

\( v_{0p} = \sqrt{v_x^2 + v_y^2} \) et \( v_{0q} = \sqrt{v_x^2 + v_y^2 + v_z^2} \)

The instantaneous active and reactive powers are given by the equation below:

\[
\begin{bmatrix}
    p \\
    q_r \\
    q_q
\end{bmatrix} = v_{0q} \begin{bmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & -1
\end{bmatrix} \begin{bmatrix}
    i_p \\
    i_q \\
    i_r
\end{bmatrix}
\]

(30)

This gives us the current in the p-q-r axis expressed by:

\[
\begin{bmatrix}
    i_p \\
    i_q \\
    i_r
\end{bmatrix} = \frac{1}{v_{0q}} \begin{bmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & -1
\end{bmatrix} \begin{bmatrix}
    p \\
    q_r \\
    q_q
\end{bmatrix}
\]

(31)

Depending on the function assigned to the filter, it is possible to compensate the harmonic current and the reactive energy or one of them at the same time. If we want to compensate the harmonic current and the reactive power, Equation 1 becomes:

\[
\begin{bmatrix}
    i_p \\
    i_q \\
    i_r
\end{bmatrix} = \frac{1}{v_{0q}} \begin{bmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & -1
\end{bmatrix} \begin{bmatrix}
    p \\
    q_r \\
    q_q
\end{bmatrix}
\]

(32)

What gives the currents in the axes a, b, c:

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix} = \begin{bmatrix}
    \frac{v_x}{v_{0a}} & \frac{v_y}{v_{0a}} & \frac{v_z}{v_{0a}} \\
    \frac{v_x}{v_{0b}} & \frac{v_y}{v_{0b}} & \frac{v_z}{v_{0b}} \\
    \frac{v_x}{v_{0c}} & \frac{v_y}{v_{0c}} & \frac{v_z}{v_{0c}}
\end{bmatrix} \begin{bmatrix}
    i_p \\
    i_q \\
    i_r
\end{bmatrix}
\]

(33)

Finally, the reference current in the axes a, b, c is obtained by the inverse Concordia transformation (Bhople & Rayarao, 2018).

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
    1 & 0 & \frac{1}{\sqrt{2}} \\
    \frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} & \frac{1}{2} \\
    -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix}
\]

(34)

2.5. The NFP-Q method

This method is based on the p-q theory with a difference that the zero sequence component of the current is separated from the zero sequence power (Andari & Beheshti, 2012; Chang & Low, 2008; Hu et al., 2015; Infield et al., 2004; Jannesar et al.; Jannesar et al., 2019). The zero sequence component is distributed over the three line currents and the compensation is independent of the zero sequence voltage. This method is intended for an equilibrium voltage network as shown in figure 5. Now, the system of currents expressed as a function of the quantities in the reference a, 0 in (.35).
With

\[ i_0(t) = \frac{1}{\sqrt{3}} (i_a + i_b + i_c) = \frac{i_n}{\sqrt{3}} \text{and} i_{in}(t) = \sqrt{3} i_0(t) \]  

We can then write the currents in the reference a, b, c as:

\[
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix}
= \sqrt{\frac{2}{3}}
\begin{bmatrix}
  0 & 0 & 0 \\
  1 & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
  \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} \\
\end{bmatrix}
\begin{bmatrix}
  i_0 \\
  i_n \\
\end{bmatrix}
\]

(37)

With this equation, the zero sequence component is separated from the current system. The currents will be treated as in a 3-wire network and we then add the zero sequence component (Hanna Nohra et al., 2019).

The reference current becomes:

\[
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix}
= \frac{1}{\sqrt{\nu^2 + \nu_p^2}}
\begin{bmatrix}
  \nu_a & -\nu_p & \nu_b \\
  \nu_p & \nu_a & 0 \\
\end{bmatrix}
\begin{bmatrix}
  \vec{v} - \vec{p} \\
  \vec{q} \\
\end{bmatrix}
\]

(38)

The current in the reference a, b, c is:

\[
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix}
= \sqrt{\frac{2}{3}}
\begin{bmatrix}
  0 & 0 & 0 \\
  1 & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
  \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} \\
\end{bmatrix}
\begin{bmatrix}
  i_n \\
\end{bmatrix}
\]

(39)

On the basis of this formulation, the zero sequence component is added to the reference currents. The new formulation of the reference current is then:

\[
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix}
= \sqrt{\frac{2}{3}}
\begin{bmatrix}
  0 & 0 & 0 \\
  1 & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
  \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} \\
\end{bmatrix}
\begin{bmatrix}
  i_n \\
\end{bmatrix}
\]

(40)
2.6. The DCAP method

The patented DCAP method proposed (Hanna Nohra et al., 2014) is based on the distribution of sinusoidal and balanced currents on the source side and not on the distribution of equal powers in the doubled source. It is developed for a polyphase system. Subsequently, we sought to determine the active sinusoidal currents desired in the source. $i_{sa}(t)$, which provides a unit power factor with a corresponding voltage even in the event of a disturbed voltage system. However, this sinusoidal current makes it possible to ensure a unit power factor with a disturbed voltage necessarily a linear relationship with the fundamental component. $v_f(t)$ disturbed voltage $v(t)$ as shown in figure 6.

\[
i_{sa}(t) = G_f v_f(t) \tag{41}\]

Or $G_f$ is the conductance of the fundamental current and voltage. It should be noted that a sinusoidal current is equivalent to its fundamental component.

The snapshots of the desired sinusoidal currents at the source in phase with their corresponding fundamental voltages are given by:

\[
\begin{align*}
    i_{sd1}(t) &= \frac{P_f}{V_f(\sum_v v_v)} V_f(1) \sqrt{2} \sin(\omega t) \\
    i_{sd2}(t) &= \frac{P_f}{V_f(\sum_v v_v)} V_f(2) \sqrt{2} \sin(\omega t - \frac{\omega}{2}) \\
    i_{sdk}(t) &= \frac{P_f}{V_f(\sum_v v_v)} V_f(k) \sqrt{2} \sin(\omega t - (k-1) \frac{\omega}{2})
\end{align*}
\]

Finally, by substituting the expression of the voltage in (II.42), the desired active currents at the source become

\[
\begin{align*}
    i_{sd1}(t) &= \frac{P_k}{V_k(\sum_v v_v)} V_k(t) \\
    i_{sd2}(t) &= \frac{P_k}{V_k(\sum_v v_v)} V_k(t) \\
    i_{sdk}(t) &= \frac{P_k}{V_k(\sum_v v_v)} V_k(t)
\end{align*}
\]

The fundamental conductance of the polyphase system is:
\[
\begin{align*}
G_{f1} &= \frac{P_1}{V_1(\sum L_v + V_b)} \\
G_{f2} &= \frac{P_2}{V_1(\sum L_v + V_b)} \\
G_{f3} &= \frac{P_3}{V_1(\sum L_v + V_b)} \\
\end{align*}
\] (44)

The system of currents in the phases is obtained as a function of the conductance as follows

\[
\begin{align*}
i_{lad}(t) &= G_{f1}V_a(t) \\
i_{lbd}(t) &= G_{f2}V_b(t) \\
i_{lcd}(t) &= G_{f3}V_c(t) \\
\end{align*}
\] (45)

By replacing the conductances with their values, it finally allows to see the desired active sinusoidal currents in the source, in phase with their fundamental voltage, and as a function of the total power in the source (Hanna Nohra et al., 2019).

\[
\begin{align*}
i_{lad} &= \frac{P_1}{V_a(\sum L_v + V_b + V_c)} V_a \\
i_{lbd} &= \frac{P_2}{V_b(\sum L_v + V_b + V_c)} V_b \\
i_{lcd} &= \frac{P_3}{V_c(\sum L_v + V_b + V_c)} V_c \\
\end{align*}
\] (46)

The reference currents can simply be deduced from the load currents and the currents in (II.80) noted:

\[i_n(t) = i_{li}(t) - i_{lad}(t)\] (47)

With \(i = a, b, c\) the phase index of the three-phase system.

In calculating the power of the load, we do not capture the fundamental components of the voltages. In fact, the instantaneous voltages which exist in the circuit are taken into account. The power of the load is (Akagi et al., 1999; Hanna Nohra et al., 2014; Harrison; Kalair et al., 2017; Kim & Akagi, 1999; Padilla-Vento, 2021)

\[P_{\text{load}}(t) = V_a(t)i_{la}(t) + V_b(t)i_{lb}(t) + V_c(t)i_{lc}(t)\] (48)

\(P_f\) is the power absorbed by the filter and required to regulate the DC bus voltage. He expresses himself thus:

\[P_f = I_0(V_{fa} + V_{fb} + V_{fc})\] (49)

The basic concept of compensation in the known methods or already classic algorithms for extracting reference currents consists of distributing the power equally over the three phases in order to balance the currents, which is not valid when the voltage are unbalanced. From these elements, the method (DCAP-Direct Control for Active Power) which is based on another approach for compensation and which makes it possible to formulate the active current (then the reference currents), in a way other than those traditionally used. We have developed thus resulting in a current-balanced system when the network is even highly unfavourable. Thus, the compensation is done in the presence of the negative sequence and zero sequence component of the network. The first author to have developed this new control approach is (Hanna et al, 2018). Subsequently, we sought to determine the desired sinusoidal active current in the source \(i(t)\) which ensures a unity power factor with its corresponding voltage \(v(t)\) even in the event of disturbance of the voltage system. However, this sinusoidal current making it possible to ensure a unity power factor with a disturbed voltage \(v(t)\) therefore has a linear relationship with the fundamental component \(v_f(t)\) of the disturbed voltage \(v(t)\).
3. System modeling
At this level, it is important to recall the spirit of the research in this work by contributing to the classification of the six algorithms for extracting reference currents according to certain indicators. To do so, the electrical system in this article will be studied in four cases of network voltage as shown in Table 1:

| Hypothesis1 | Hypothesis2 | Hypothesis3 | Hypothesis4 |
|-------------|-------------|-------------|-------------|
| Va = 380 V  | Va = 380 V  | Va = 380 V  | Va = 380 V  |
| Vb = 380 V  | Vb = 325 V  | Vb = 380 V  | Vb = 325 V  |
| Vc = 380 V  | Vc = 410 V  | Vc = 380 V  | Vc = 410 V  |
| V5 = 0      | V5 = 0      | V5 = 30 V   | V5 = 30 V   |

Hypothesis 1: Sinusoidal and balanced voltage.
Hypothesis 2: Sinusoidal and unbalanced voltage.
Hypothesis 3: Balanced and disturbed voltage.
Hypothesis 4: Unbalanced and disturbed voltage.

The synoptic of the TLC hybrid filter will as shown in Figure 7 be studied in its four cases with several sought-after objectives which will be developed and commented in our results. On the other hand, the constituted voltage system consists of a fundamental voltage and the harmonic of the order 5, \( V_{0.5} \) expressed as follows:

\[
\begin{align*}
V_a(t) &= V_{af} + V_{a.5} \\
V_b(t) &= V_{bf} + V_{b.5} \\
V_c(t) &= V_{cf} + V_{c.5}
\end{align*}
\]

(50)

With as expressions of the fundamental quantities:

\[
\begin{align*}
V_{af}(t) &= V_{af} \sin(wt) \\
V_{bf}(t) &= V_{bf} \sin(wt - \frac{\pi}{3}) \\
V_{cf}(t) &= V_{cf} \sin(wt + \frac{2\pi}{3})
\end{align*}
\]

(51)

\[
\begin{align*}
V_{a.5}(t) &= \hat{V}_5 \sin(5wt) \\
V_{b.5}(t) &= \hat{V}_5 \sin(5wt - \frac{2\pi}{3}) \\
V_{c.5}(t) &= \hat{V}_5 \sin(5wt + \frac{\pi}{3})
\end{align*}
\]

(52)

And order 5 harmonic voltages taken in positive sequence as follows:

With \( \hat{V}_5 \) is the maximum amplitude of the order harmonic 5.

Table 1 shows the numerical values of the voltage in the four cases studied.

The filter parameters used in the rest of our work have become in the following Table 2
4. Result and discussion
It is important to remember at this level that a fourth connection is made on the neutral wire to observe the behavior of that over time for the four operating hypotheses.
4.1. Original PQ method

Figure 8(a) shows a THD of 1.73% and UFI of 0.33% satisfactory results compared to the standard (IEEE 519–2014) for voltage below 69kv, for a THD between 3% and 5%. And the EN 50160 standard which requires an UFI of less than 2%. Hypotheses 2, 3, 4, respectively, present 1.79%; 2%; 0.33% in THD results also in accordance with the standard. On the other hand in UFI boxes 2.3 present respectively 5.33%, 16.66% which are of poor quality with regard to the requirements of the standard above and finally case 4 which offers 1.73% which on the other hand is validated by

Figure 8. Results with the original PQ method for current (ia, ib, ic) and neutral current for 4 hypothesis (A, B, C, D, E, F, G, H).
Hypothesis 3

E

Hypothesis 4

F

G

H
the standard in force stated above. Figure 8 also shows the evolution of the current in the neutral for each case.

4.2. Results with the modified PQ method

Figure 9 shows, respectively, THDs of: 1.73%, 2%, 1.8%, 1.7% for hypothesis 1, 2, 3, 4, which also comply with the IEEE 519–2014 standard; on the other hand, only case 1 has a UFI of 0.33% which also conforms to the standard but cases 2, 3.4 present, respectively, 5%; 8.33% and 3.33%, which are not of good quality in accordance with the standard. Any time on the remark that the modified PQ method succeeded in improving by half the case 3. With a UFI of 8.33%, it seems to be the most indicated method for this hypothesis of functioning.

Figure 9. Results with the modified PQ method for current (ia, ib,ic) and neutral current for 4 hypothesis (A1, B1, C1, D1, E1, F1, G1, H1).
4.3. P-q pseudo-mapping matrix method

Figure 10 shows THDs of: 1.73%, 2.1%, respectively; 0.33%; 2% for cases 1, 2, 3, 4, which are also satisfactory for the IEEE 519–2014 standard, on the other hand only cases 1, 3 have a UFI of 0.33% and 1.76% which also conforms to the standard but cases 2, 4 show 20%, respectively; 13.76%, which are not of good quality in accordance with the standard. Any time we notice that the pq pseudo-mapping matrix method succeeds in improving box 3 by half better than the first two methods with an UFI of 1.76%. It seems to be the method which ise most suitable for this operating hypothesis.
4.4. Simulation results for p-q-r method

Figure 11 shows, respectively, THDs of: 1.73%, 2.12%; 1.73%; 2.23% for cases 1, 2, 3, 4, which also comply with the IEEE 519–2014 standard; on the other hand, only cases 1 and 3 have a UFI of 0.33% and 0.66%, which also conform to the standard but cases 2 and 4 present 28.33%, and 36.2%, respectively, which are not of good quality in accordance with the standard. Any time on the remark, the PQR method succeeds in improving case 3 with a UFI of 0.66%, it seems to be the most indicated method compared to the first three methods for this working hypothesis.
4.5. Simulation results for the NFP-Q theory

Figure 12 shows, respectively, THDs of: 1.73%, 1.95%, 1.74%, 1.95% for cases 1, 2, 3, 4, which also comply with the IEEE 519-2014 standard, on the other hand only cases 1 and 3 have an UFI of
0.33% and 1%, which also comply with the standard but cases 2 and 4 present, respectively, 16.66% and 16.66%, which are not of good quality in accordance with the standard. Any time on the remark that the PQ R method succeeds in improving case 3 with a UFI of 1%, it seems to be the most indicated method compared to the first three methods for this hypothesis operating. But it is also important to note that the PQR method gives us a result of 0.66% UFI, which remains a better result than that obtained with the NFPQ method.

4.6. Simulation results for the DCAP method

Figure 13 shows, respectively, THDs of: 1.73%, 1.73%, 1.73%, and 1.74% for cases 1, 2, 3, and 4, which also comply with the IEEE 519–2014 standard, on the other hand only cases 1, 2, 3, and 4
have an UFI of 0.33%, 0.66 %, 0.66%, 1, respectively, which also conform to the standard. On its own, it succeeds in giving satisfaction for cases 1, 2, 3, and 4 with a better result in case 4 compared to all the methods developed. The DCAP algorithm therefore stands out as being the best for all network operating conditions in this job. The research spirit of this article is to contribute to a classification of six algorithms for extracting reference currents within the
framework of harmonic compensation for a stochastic electrical network which for the particular case of this work presents four configurations. A general presentation of all the parameters or indicators is concentrated in a table with the objective also to facilitate the discussion, but above all to validate the results obtained.
5. Validation of results
A double-level validation will be carried out: firstly the IEEE-519-2014 standard will be used as a benchmark, secondly a validation through certain authors such as (“IEEE Recommended Practice and Requirements,” 2014) as shown in table 3.

The original PQ method offers 100% satisfaction for the hypotheses (1, 2, 3, and 4) in THD, which all comply with the standard (IEEE 519–2014) on the other hand, it is satisfactory at 50% hypotheses (1, 2, 3,4) for the UFI value as shown in table 4. It is better than the modified PQ which offers 25% satisfaction
for the UFI value for the hypotheses (1, 2, 3, 4), however we notice that the quality in THD is better for the modified PQ for the hypotheses (1, 2, 3, 4) in comparison with the original PQ. Results are comforted by the work of (LI-WANG et al 2018). The observation is the same for the pq Mapping-matrix method which also offers 50% of UFI for the hypotheses (1, 2, 3, 4) and 100% for the THD being the same assumptions. We can also see that the quality in THD is less good than the first two methods. Results also reassured by

Figure 13. Simulation results for the DCAP theory for current (ia, ib, ic) and neutral current for 4 hypothesis (A5, B5, C5, D5, E5, F5, G5, H5).
the work of (HANNA et al. 2018). On the other hand, the NFPQ and PQR methods are at 50% and 100%, respectively, for their THD and common UFI for the hypotheses (1, 2, 3, 4) defined. Finally, the DCAP method which offers 100% satisfaction in THD and UFI for the hypotheses (1, 2, 3, 4), which in the end, appears as the most satisfactory extraction method. These results are supported by the work of (Hanna Nohra et al., 2014).
Table 3. Summary table of simulation results

| Methods                  | Hypothesis 1 | Hypothesis 2 | Hypothesis 3 | Hypothesis 4 |
|--------------------------|--------------|--------------|--------------|--------------|
| P-q original             | \(i_{s_1}\)   | \(i_{s_2}\)   | \(i_{s_3}\)   | \(i_{s_4}\)   |
| P-Q modifiée             | \(i_{s_1}\)   | \(i_{s_2}\)   | \(i_{s_3}\)   | \(i_{s_4}\)   |
| Method PQR               | \(i_{s_1}\)   | \(i_{s_2}\)   | \(i_{s_3}\)   | \(i_{s_4}\)   |
| NFPQ                     | \(i_{s_1}\)   | \(i_{s_2}\)   | \(i_{s_3}\)   | \(i_{s_4}\)   |
| Method DCAP              | \(i_{s_1}\)   | \(i_{s_2}\)   | \(i_{s_3}\)   | \(i_{s_4}\)   |
| UFI                      | 0.33%         | 5.33%         | 16.66%        | 0.33%         |
| THD                      | 1.73%         | 1.79%         | 2%            | 1.73%         |
| UFI                      | 0.33%         | 5%            | 8.33%         | 3.33%         |
| THD                      | 1.73%         | 2%            | 1.8%          | 1.77%         |
| UFI                      | 0.33%         | 20%           | 0.33%         | 13.66%        |
| THD                      | 1.73%         | 2.10%         | 1.73%         | 2%            |
| UFI                      | 0.33%         | 28.33%        | 0.66%         | 32.66%        |
| THD                      | 1.73%         | 2.12%         | 1.73%         | 2.23          |
| UFI                      | 0.33%         | 16.66%        | 1%            | 16.66%        |
| THD                      | 1.73%         | 1.95%         | 1.74%         | 1.95%         |
| UFI                      | 0.33%         | 0.66%         | 0.66%         | 1%            |
| THD                      | 1.73%         | 1.73%         | 1.73%         | 1.74%         |
Table 4. Validation table in accordance with IEEE-519-2014

| Methods            | Hypothesis 1 | Hypothesis 2 | Hypothesis 3 | Hypothesis 4 |
|--------------------|--------------|--------------|--------------|--------------|
| P-q original       | Yes          | No t         | No t         | Yes          |
| UFI                | Yes          | Yes          | Yes          | Yes          |
| THD                | Yes          | Yes          | Yes          | Yes          |
| P-Q modifiée       | Yes          | No t         | No t         | No t         |
| UFI                | Yes          | Yes          | Yes          | Yes          |
| THD                | Yes          | Yes          | Yes          | Yes          |
| p-q Mapping-matrix | Yes          | No t         | Yes          | No t         |
| Methode PQR        | Yes          | No t         | Yes          | No t         |
| NFQR               | Yes          | Yes          | Yes          | Yes          |
| UFI                | Yes          | No t         | Yes          | No t         |
| THD                | Yes          | Yes          | Yes          | Yes          |
| Methode DCAP       | Yes          | Yes          | Yes          | Yes          |

6. Conclusion

In this article, it was a question of making a contribution to the classification of six algorithms for extracting reference currents for harmonic compensation with the TLC hybrid filter under operating conditions in sinusoidal and balanced voltage, sinusoidal and unbalanced voltage, voltage balanced and disturbed. Finally in unbalanced and disturbed tensions with the ultimate goal of determining the algorithm best suited to the disturbances that the electrical network may undergo. Thus, offering the possibility of optimizing the sequence or the compensation step by injection into the electrical network thanks to a robust and reliable extraction algorithm. Harmonic voltage of order 5 taken in positive sequences were used during the execution or compilation of these six algorithms. And it emerges that the algorithm of the DCAP method is positioned as being the extraction technique which resists the most disturbances with results both validated by standard IEEE 519–2014 and EN 50160; on the other hand (Hanna Nohra et al., 2014), which in its work with active compensators already presented the advantages of this new approach for extracting reference currents. These results are reinforced in the four operating conditions developed for our case study.

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The data which contributed to the realization of this article are at the same time in the number of the literature but also of the protocols of several experimental tests in laboratories, thus the possible submissions for publications.
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