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Evaluation of the Shunt Active Power Filter apparent power ratio using particle swarm optimization

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The main objective of this present paper is the study of the Shunt Active Power Filter (APF) compensations capability for different perturbations in AC power system such as current unbalance, phase shift current and undesired harmonics generated by nonlinear load and/or by the power system voltage. This capability is determined by the maximum rate of the apparent power that can be delivered. This study is based on the definition of the effective apparent power as defined in IEEE 1459-2000 which was proved to be the suitable amount to be concerned in the design process of different devices.

Key words: effective apparent power, shunt active power filter, particle swarm optimization, harmonics, unbalanced voltages, unbalanced load

1. Introduction

Evolution of industrial power electrical equipments, due to the large demands and requirements of different consumers has contributed intensively into the degradation of the power quality in AC power system with a drastically manner. The proliferation of nonlinear load, unbalanced load, large single phase loads, and voltage unbalance of one or more phases can frequently occur [1]. The current distortion and/or unbalance may cause undesirable effects on the power system operation, especially when the sensitive loads are used [2-7]. Furthermore, an unbalanced power system voltage can worsen drastically the power quality, practically with power electronics converters, AC machines and other equipments. In industrial application, where three phase rectifiers are intensively used, the unbalance currents due to unbalanced power supply voltage causes harmful effects leading to an uneven current distribution over the rectifier bridge legs which increases the conduction loss and may cause failure of rectifying devices, increased Real Mean Square (RMS) ripple current in the smoothing capacitor, increased total RMS line current and harmonics, in particular, noncharacteristic triplen harmonics that do not appear under balanced condition [8-11]. Thus the power ratings of filters and switches are in-

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creased due to the power supplied by the source. On the other side an unbalanced voltage system supplied to an AC machine generates large negative-sequence which can increase the machine losses and reduces the machine use qualification [12, 13].

The Shunt APFs are presently the powerful tools and the most versatile and effective solution to face up to the challenge of reducing or eliminating the undesired current disturbances, protecting electrical equipment which could be affected by poor power quality and avoiding the propagation of generated disturbances to be followed toward the source or power supply. On the other side, these devices can achieve the compensation of reactive power and unbalance of nonlinear and fluctuating loads.

A perfect power quantity and quality supply would be one that is always available within voltage and frequency tolerances, and has a pure sinusoidal wave shape. The deviation from this perfection which can be accepted depends on the user's application and their requirements. Users are faced extremely with the exact need for making design investment decisions about the quantity of the compensation power of the Shunt APF required to achieve the quality of power delivered by the power system source. This study will give an approach for the evaluation of the power compensation in a way to allow for the manufacturer to determine the Shunt APF devices dimension and to the users to get an optimum technical economical choice. In the present work, the new definition of the apparent power defined in IEEE 1459-2000 is used in order to evaluate of the Shunt APF, in a way to avoid the errors which were made in the last years when the apparent power was evaluated using classical definitions [14-17]. The main aim is to minimize the dimensions of the used devices and to achieve the power requirement compensation at the same time. In this study it is supposed that the power system voltage is unbalanced under practical tolerances.

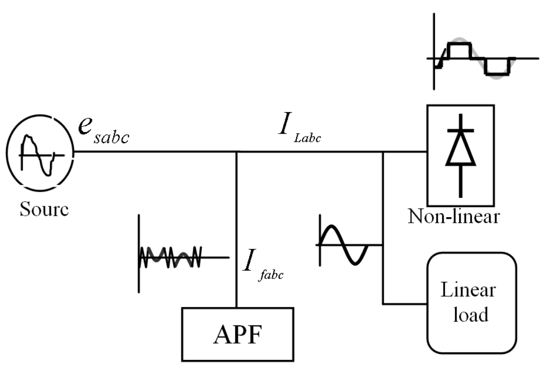

Figure 1. Shunt Active Power Filter principle schematics.

2. Shunt Active Power Filter

Active Power Filter (APF) is a power electronics device based on the use of power electronics inverters (Fig. 1). The Shunt APF is connected in the point of common connection (PCC) between the source of power system and the load system which present the source of the polluting currents circulating in the power system lines[13-15],[18-20]. This insertion as it is presented in Fig. 2 is realized via a low pass filter such as, L, LC or LCL filters [7].

The Shunt APF injects current components in the power system in a small amount of power by ratio of the power delivered by the source to load. The compensating power can dynamically suppress the distorted current component, eliminate the components contributing in the current unbalance and make the currents circulating toward the power source to be in phase with the direct voltage sequence of the power system voltage. The result of this is that the utility currents after the compensation become sinusoidal, balanced and with the desired amplitudes and phase shift. The fundamental equation representing the principle of the shunt APF compensation is given by:

$$I_{Labc} = I_{fabc} + I_{Sabc} \tag{1}$$

where

$$I_{Labc} = \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix}, \quad I_{fabc} = \begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix}, \quad I_{Sabc} = \begin{bmatrix} I_{Sa} \\ I_{Sb} \\ I_{Sc} \end{bmatrix}. \tag{2}$$

3. Shunt Active Power Filter apparent power

To clarify this study a general case was studied theoretically for three phase three wire systems, and then special cases which can be occur in industrial loads were derived, such as current harmonics, unbalance and/or distorted currents. Practically each case has its own calculation to achieve exactly the compensation needed to improve the power quality of the source power system. Moreover, lots of studies have been pursued on Shunt APF. But in most of them, the supply voltage is considered as a sinusoidal variable with constant amplitude [17] [21-24]. In the present study, as the supply-voltage unbalance is very serious problem for the load, especially due to the appearance of the negative sequence [25-26], the unbalance of line voltage must be taken into account as a design factor in the Shunt APF. Therefore, the power system voltage is expressed by:

$$\begin{aligned} v_a &= \sqrt{2}k_aV\sin\left(\omega t + \phi_a\right) \\ v_b &= \sqrt{2}k_bV\sin\left(\omega t + \phi_b - \tfrac{2\pi}{3}\right) \\ v_c &= \sqrt{2}k_cV\sin\left(\omega t + \phi_c + \tfrac{2\pi}{3}\right) \end{aligned} \tag{3}$$

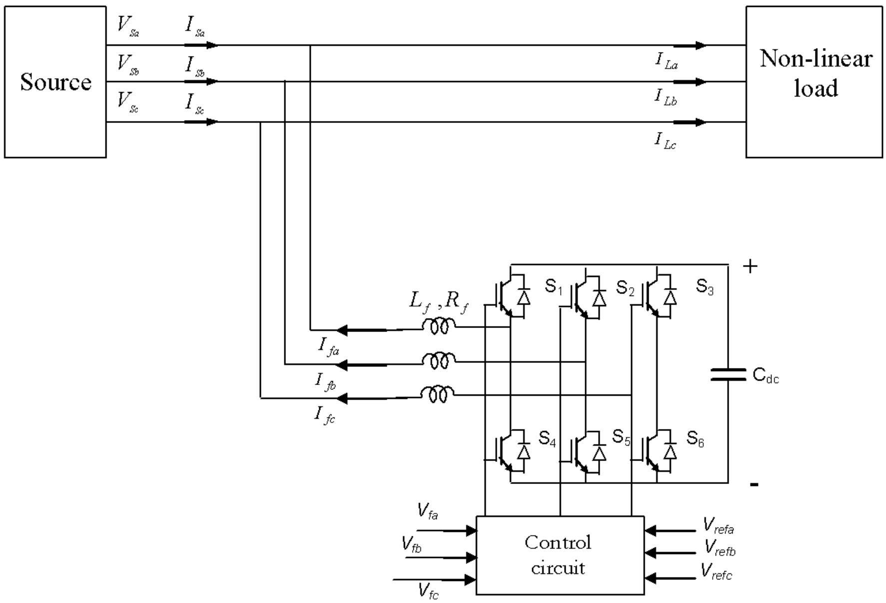

Figure 2. Three wire schematics of the Shunt APF.

where k_a, k_b and k_c are the magnitude voltage unbalance factors; ϕ_a, ϕ_b and ϕ_c are the phase shift unbalance for the phases a, b and c. The h'th component of the load currents are then defined as follows:

$$\begin{aligned} i_{ah} &= \sqrt{2}k_a k'_a I_{Mh} \sin\left(h\omega t + \gamma_{ah}\right) \\ i_{bh} &= \sqrt{2}k_b k'_b I_{Mh} \sin\left(h\left(\omega t - \frac{2\pi}{3}\right) + \gamma_{bh}\right) \\ i_{ch} &= \sqrt{2}k_c k'_c I_{Mh} \sin\left(h\left(\omega t + \frac{2\pi}{3}\right) + \gamma_{ch}\right) \end{aligned} \tag{4}$$

where k'_a, k'_b and k'_c are the magnitude currents unbalance factors; γ_{ah}, γ_{bh} and γ_{ch} are the phase shift unbalance for the phases a, b and c load currents; h presents the harmonics order $h = 1, 2, \ldots$; I_{Mh} is the current magnitude of the h'th harmonics, it is the same for the all three phases. The magnitudes unbalances of the different harmonics components of the three phases depend on k'_a, k'_b, k'_c and k_a, k_b, k_c, respectively.

The necessary apparent power which responds to the load requirement following to the effective apparent definition is expressed as [18-20], [27-38]:

$$S_e = 3V_e I_e \tag{5}$$

where V_e and I_e are the corresponding effective voltage and effective current of the power supplied being applied to the load which are calculated as follows:

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}} = \sqrt{I_{e1}^2 + I_{eh}^2} \tag{6}$$

where

$$I_{e1} = \sqrt{\frac{I_{a1}^2 + I_{b1}^2 + I_{c1}^2}{3}}, \quad I_{eh} = \sqrt{\frac{I_{ah}^2 + I_{bh}^2 + I_{ch}^2}{3}} \tag{7}$$

I_{e1} is the fundamental component effective current; from (4) and (7) it can be expressed as:

$$I_{e1} = \frac{I_M}{\sqrt{3}} \sqrt{k_a^2 k_a'^2 + k_b^2 k_b'^2 + k_c^2 k_c'^2}. \tag{8}$$

The effective voltage of the three-wire power system is expressed as [37-39]:

$$V_e = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{3}} \tag{9}$$

V_{ab}, V_{bc} and V_{ca} are the inter phase magnitudes.

From (3) and (9) the effective voltage of the power supply can be presented as follow:

$$V_e = \frac{V}{3} \sqrt{2\left(k_a^2 + k_b^2 + k_c^2\right) - \Delta V} \tag{10}$$

where:

$$\Delta V = \sum_{\substack{i,j=a,b,c \\ i \neq j}}^{a,b,c} k_i k_j \cos\left(\left|\phi_i - \phi_j\right| + \frac{2\pi}{3}\right). \tag{11}$$

In Fig. 3 and Fig. 4 the effective voltage is presented in case of one phase unbalance and two phase unbalance respectively versus different phase shift unbalance.

From (5) and (6) the effective apparent power can be presented by:

$$S_e^2 = 9V_e^2 I_e^2 = 9V_e^2 I_{e1}^2 + 9V_e^2 I_{eh}^2 \tag{12}$$

$$S_e^2 = S_{e1}^2 + S_{eh}^2 \tag{13}$$

S_{eh} is the apparent power responsible of different harmonics contained in the load current. On the other side the effective apparent power due to the fundamental component of the current is calculated as follow:

$$S_{e1}^2 = 9V_e^2 I_{e1}^2. \tag{14}$$

This power contains two parts:

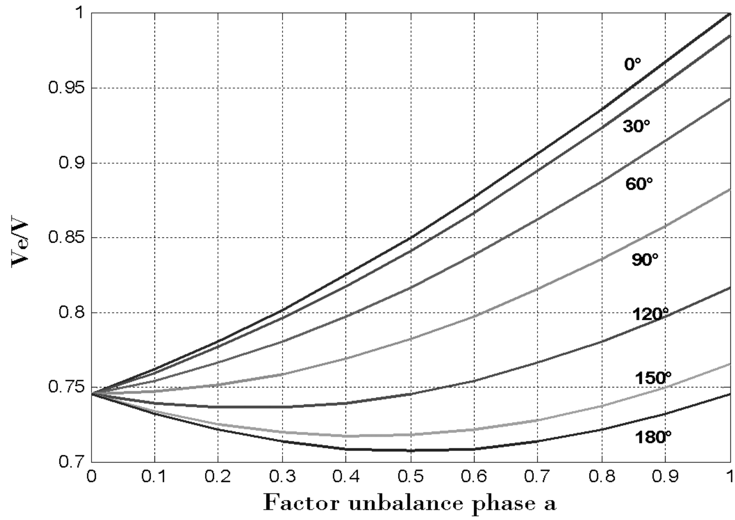

Figure 3. The effective voltage when one phase unbalance is occurred.

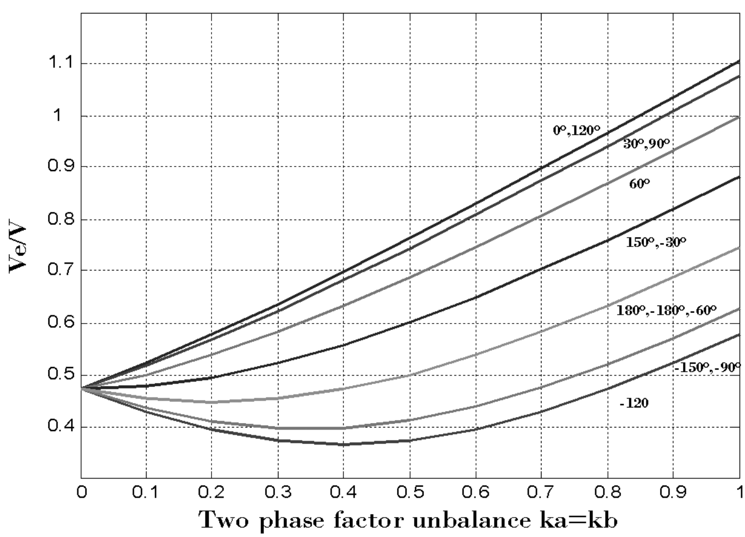

Figure 4. The effective voltage when similar Two phase unbalances are occurred.

- A component due to the fundamental positive component of current; it is the one generated by the power system to the load. This power is given by:

$$S_{e1}^{+} = 3V_e I_{e1}^{+}. \tag{15}$$

- A component due to the negative and zero components of the current; it is the one responsible for the unbalance in the load side. The Shunt APF must produce and inject this power to eliminate the unbalance of the current absorbed from the source of the power system. This power is given by:

$$S_{unb}^2 = S_{e1}^2 - {S_{e1}^+}^2. \tag{16}$$

The effective fundamental positive component of the effective current is given by:

$$I_{e1}^+ = \frac{I_M}{3}\sqrt{k_a^2 {k'_a}^2 + k_b^2 {k'_b}^2 + k_c^2 {k'_c}^2 + \Delta I} \tag{17}$$

where:

$$\Delta I = \sum_{\substack{i,j=a,b,c \\ i \neq j}}^{a,b,c} k_i k'_i k_j k'_j \cdot \cos(\phi_i + \gamma_i - \phi_j - \gamma_j) \tag{18}$$

ϕ_i, ϕ_j, γ_i and γ_j are the fundamental voltages and currents phase shifts in the three phases.

In Fig. 5 and Fig. 6 the fundamental positive sequence effective current is presented following two cases, for one phase voltage and current unbalances and for two phases' voltage and current unbalances respectively.

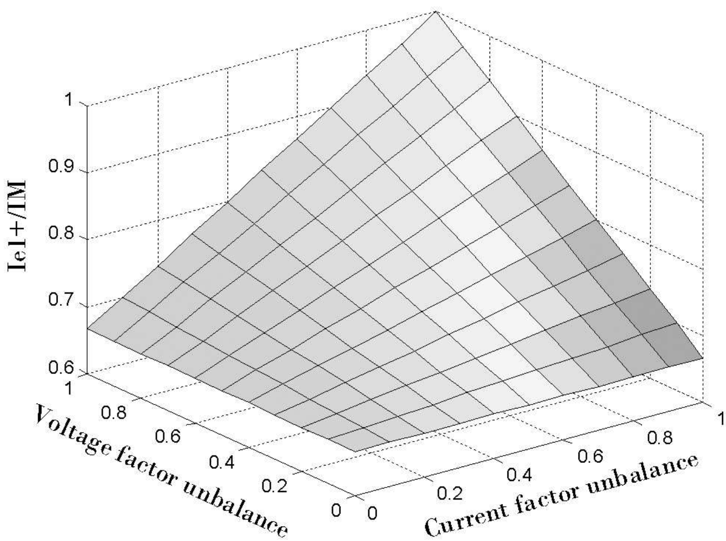

Figure 5. The fundamental positive sequence effective current for the same one phase voltage unbalance and current unbalance.

The effective apparent power responsible of the unbalance in the load currents is expressed by:

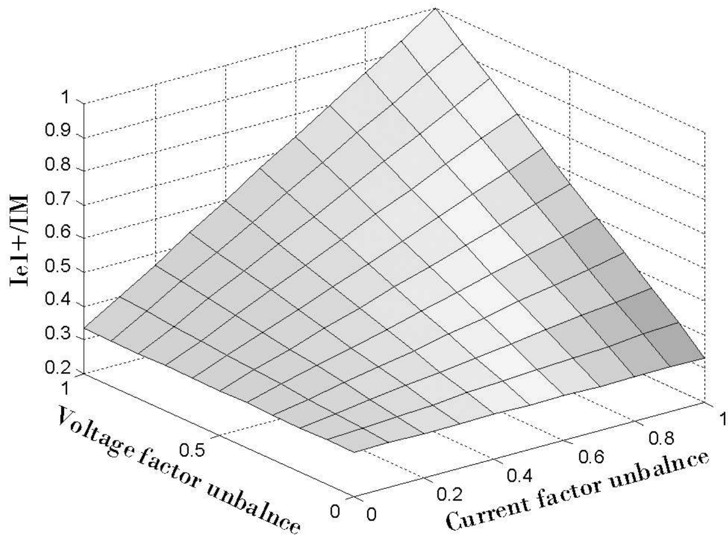

Figure 6. The fundamental positive sequence effective current for the same one phase voltage unbalance and current unbalance of two different phases.

$$S_{unb} = 3V_e \cdot \sqrt{I_{e1}^2 - I_{e1}^{+\,2}}. \tag{19}$$

It can be written as:

$$S_{unb} = V_e \cdot I_M \cdot \sqrt{2 \cdot \Delta k - \Delta I} \tag{20}$$

where:

$$\Delta k = k_a^2 k_a'^2 + k_b^2 k_b'^2 + k_c^2 k_c'^2. \tag{21}$$

The power responsible for different harmonics contained in the load current is given by:

$$S_{eh} = 3V_e \cdot I_{eh} \tag{22}$$

where the effective harmonic current is:

$$I_{eh} = I_h \sqrt{\frac{k_a^2 k_a'^2 + k_b^2 k_b'^2 + k_c^2 k_c'^2}{3}}, \tag{23}$$

$$I_{eh} = I_h \sqrt{\frac{\Delta k}{3}}. \tag{24}$$

From equations (8) and (21), equation (24) can be written as:

$$I_{eh} = I_h \cdot \frac{I_{e1}}{I_M} = THD_e^I \cdot I_{e1} \tag{25}$$

THD_e^I is the total harmonic distortion of the load current, it is presented by σ so :

$$S_{eh} = 3V_e \cdot \sigma \cdot I_{e1}, \tag{26}$$

$$S_{eh} = \sqrt{3} V_e I_M \cdot \sigma \cdot \sqrt{\Delta k}. \tag{27}$$

Finally in order to achieve the power factor in the source equal to 1, the reactive power needed by the load have to be canceled with the fundamental components of voltage and current. Thus the Shunt APF has to generate the apparent power needed so that the voltages in the three phases have the same phase shift angles as the currents absorbed from the source by the load in the corresponding three phases. Fig. 7 shows the case of the phase *a*.

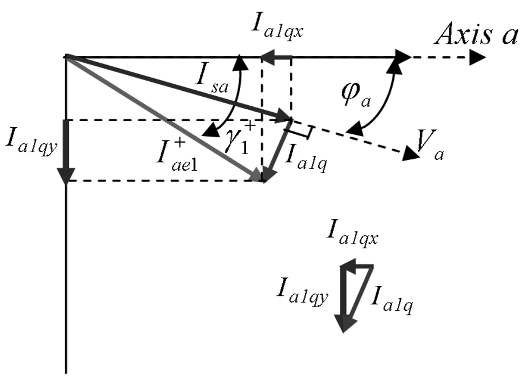

Figure 7. The phase shift elimination (phase *a*).

The magnitude of the positive sequence of the current is the same as the magnitude of the effective positive sequence:

$$\begin{bmatrix} I_{a1}^+ \\ I_{b1}^+ \\ I_{c1}^+ \end{bmatrix} = \begin{bmatrix} I_{e1}^+ \\ I_{e1}^+ \\ I_{e1}^+ \end{bmatrix}. \tag{28}$$

The currents needed to achieve the elimination of the reactive power to be absorbed from the power system are I_{a1q}^+, I_{b1q}^+ and I_{c1q}^+. To obtain the minimum magnitude of these components they must be perpendicular on the source currents of the corresponding phases as it is shown in Fig. 7; the magnitude of these currents are then:

$$\begin{bmatrix} I^+_{a1q} \\ I^+_{b1q} \\ I^+_{c1q} \end{bmatrix} = I^+_{e1} \cdot \begin{bmatrix} \sqrt{1-\cos\left(\phi_a - \gamma^+_1\right)} \\ \sqrt{1-\cos\left(\phi_b - \gamma^+_1\right)} \\ \sqrt{1-\cos\left(\phi_c - \gamma^+_1\right)} \end{bmatrix}. \tag{29}$$

The effective current of these components can be evaluated as:

$$I^+_{e1q} = I^+_{e1} \cdot \sqrt{1 - \frac{\sum\limits_{i=a,b,c} \cos\left(\phi_i - \gamma^+_1\right)}{3}} \tag{30}$$

or

$$I^+_{e1q} = I^+_{e1} \cdot \Delta q \tag{31}$$

where:

$$\Delta q = \sqrt{1 - \frac{\sum\limits_{i=a,b,c} \cos\left(\phi_i - \gamma^+_1\right)}{3}}. \tag{32}$$

The corresponding effective apparent power responsible for the phase shift between the power system voltage and the load current is expressed as:

$$S^+_{e1q} = 3 \cdot V_e . I^+_{e1q}. \tag{33}$$

This leads to the following expression:

$$S^+_{e1q} = S^+_{e1} \cdot \sqrt{1 - \frac{\sum\limits_{i=a,b,c} \cos\left(\phi_i - \gamma^+_1\right)}{3}}. \tag{34}$$

Finally it can be written as:

$$S^+_{e1q} = V_e I_M \cdot \sqrt{\Delta k + \Delta I} \cdot \Delta q. \tag{35}$$

The total apparent power necessary to achieve a good compensation for the unbalances, harmonics and reactive power is deduced from equations (20), (27) and (35). It is presented by the following expression:

$$S_{comp} = \sqrt{S^2_{unb} + S^2_{eh} + {S^+_{e1q}}^2} \tag{36}$$

so:

$$S_{comp} = V_e I_M \sqrt{S_{comp1} + S_{comp2}} \tag{37}$$

where:

$$S_{comp1} = \Delta k \cdot \left(2 + 3 \cdot THD_e^{I\,2} + \Delta q^2\right), \tag{38}$$

$$S_{comp2} = \left(\Delta q^2 - 1\right) \cdot \Delta I. \tag{39}$$

The positive apparent power ratio is supposed as:

$$R_p = \frac{S_{e1}^{+}}{S_{e1}}. \tag{40}$$

This can be written as:

$$R_p = \frac{I_{e1}^{+}}{I_{e1}} \tag{41}$$

or:

$$R_p = \frac{1}{\sqrt{3}} \cdot \sqrt{1 + \frac{\Delta I}{\Delta k}} \tag{42}$$

where:

$$0 \prec R_p \leqslant 1. \tag{43}$$

Practical values of R^{+} are not far from 1.

The main objective of the work described in this paper is to obtain the apparent power ratio of the Shunt APF which characterizes its capability for achieving the main aim of compensation. This ratio is presented as follows:

$$R = \frac{S_{comp}}{S_s} \tag{44}$$

where:

$$S_s = 3 \cdot V_e \cdot I_{se} \tag{45}$$

presents the apparent power delivered by the power system (source) to the load with an optimized cost. I_{se} is the effective current circulating from the source to the PCC, it can be calculated by:

$$I_{se} = \sqrt{\frac{I_{sa}^2 + I_{sb}^2 + I_{sc}^2}{3}} \tag{46}$$

where:

$$\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} = I_{e1}^{+} \cdot \begin{bmatrix} \cos\left(\phi_a - \gamma_1^{+}\right) \\ \cos\left(\phi_b - \gamma_1^{+}\right) \\ \cos\left(\phi_c - \gamma_1^{+}\right) \end{bmatrix}. \tag{47}$$

The effective source current is then:

$$I_{se} = I_{e1}^{+} \cdot \Delta\beta \tag{48}$$

where:

$$\Delta\beta = \sqrt{\frac{\sum\limits_{i=a,b,c} \cos^2\left(\phi_i - \gamma_1^{+}\right)}{3}}. \tag{49}$$

The apparent power of the source is:

$$S_s = 3 \cdot V_e \cdot I_{e1}^{+} \cdot \Delta\beta = S_{e1}^{+} \cdot \Delta\beta. \tag{50}$$

The compensation apparent power products by the APF is:

$$S_{comp} = \frac{S_{e1}^{+}}{R_p}\sqrt{1+\sigma^2+{R_p}^2\cdot\left(\Delta q^2-1\right)}. \tag{51}$$

The apparent power ratio of the Shunt APF can then be written by the following expression:

$$R = \frac{1}{R_p \cdot \Delta\beta} \cdot R_0 \tag{52}$$

where:

$$R_0 = \sqrt{1+\sigma^2+{R_p}^2\cdot\left(\Delta q^2-1\right)}. \tag{53}$$

R gives a clear idea about the Shunt APF dimension to fulfill the desired compensations, it can also be used in the process design of the devices used in this compensators. In this study the loses due to the devices operations such as the switching lose of static switches were not taken into account, as it is neglected beyond the apparent power needed by the compensation.

4. Evaluation of the apparent power ratio of the Shunt APF with disturbances of particular cases

The following cases give examples of the apparent power ratio of the Shunt APF in special cases of disturbances in three phase three wire AC power system. It is supposed in these cases that the power system voltages are balanced.

Case I: one phase unbalanced load. The following values are taken to calculate the different parameters used in the evaluation of the power ratio:

$$k_a = k_b = k_c = 1, \quad k'_b = k'_c = 1, \quad k'_a = k$$
$$\phi_a = \phi_b = \phi_c = 0, \quad \gamma_b = \gamma_c = 0, \quad \gamma_a = \gamma, \quad \sigma = 0.$$

The following figures give the values of the power ratio R of the Shunt APF, and the positive sequence apparent power ratio R_p. It is clear from Fig. 8, that the power ratio equals 0, when there is no unbalance in phase a, this means that the load is linear and the load currents are balanced. There is no need for the Shunt APF compensation. The positive sequence power ratio can be written as:

$$R_p = \frac{1}{\sqrt{3}} \cdot \sqrt{1 + \frac{4k'_a \cdot \cos(\gamma_a) + 2}{{k'_a}^2 + 2}}. \tag{54}$$

It gives a clear image about the effect of the unbalance in the load current, when this ratio is close to 1, the compensation apparent power of the Shunt APF is close to zero and the compensation needed is minimal.

R depends on R_p, $\Delta\beta$ and R_0 where:

$$\Delta\beta = \cos\left(\gamma_1^+\right),$$
$$\gamma_1^+ = a\tan\left(\frac{k'_a \cdot \sin(\gamma_a)}{k'_a \cdot \cos(\gamma_a) + 2}\right),$$
$$R_0 = \sqrt{1 + {R_p}^2 \cdot (\Delta q^2 - 1)},$$
$$\Delta q = \sqrt{1 - \cos\left(\gamma_1^+\right)}.$$

$\Delta\beta$ presents the effect of the phases shift of voltages power system and the fundamental positive sequence of the current. Therefore, in the present case if $\gamma_a = 0$ then:

$$\begin{cases} \Delta\beta = 0 \\ \Delta q = 0 \\ R_0 = \sqrt{1 - R_p^2}, \end{cases} \tag{55}$$

Finally:

$$R = \sqrt{\frac{1}{R_p^2} - 1}. \tag{56}$$

It is clear that R depends only on R_p. In Fig. 8 and Fig. 9 it is shown clearly for $k = 1$ (balanced load currents) that:

$$\begin{cases} R_p = 1 \\ R = 0 \end{cases} \quad \text{Hence no compensation is needed.}$$

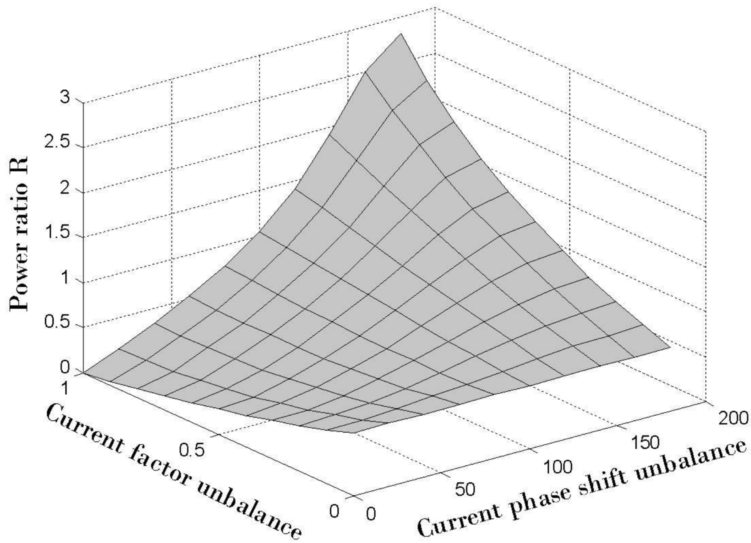

Figure 8. Power ratio when one phase unbalance current is occurred.

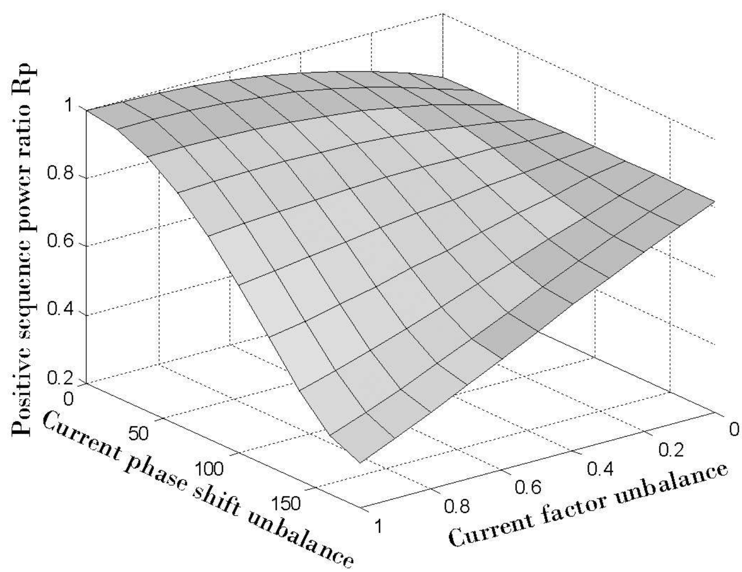

Figure 9. Positive sequence power ratio when one phase unbalance current is occurred.

Case II: Two phase unbalanced load. The following parameters are used in the evaluation of the power ratio:

$$k_a = k_b = k_c = 1, \quad k'_b = k, \quad k'_a = k, \quad k'_c = 1$$
$$\phi_a = \phi_b = \phi_c = 0, \quad \gamma_a = \gamma_b = \gamma_c = 0, \quad \sigma = 0.$$

It is clear from Fig. 10, that the power ratio equals to 0 for $k'_a = k'_b = 1$. This means that no compensation is needed for balanced power system voltages and balanced linear load currents. This value is maximal when the currents of phases b and c are zero; in this case the power compensation needed from the Shunt APF is nearly twice the power produced by the power system to make the power system currents to be balanced. These results are given with linear loads, but such constraints are far from practical cases and leads the shunt APF to be useless. The positive sequence power ratio in this case is given by:

$$R_p = \frac{1}{\sqrt{3}} \cdot \sqrt{1 + \frac{2k^2 + 4k}{2k^2 + 1}}. \tag{57}$$

R depends in this case only on R_p and R_0:

$$R = \frac{R_0}{R_p} \tag{58}$$

where:

$$\begin{cases} \Delta\beta = 1 \\ \gamma_1^+ = 0 \\ R_0 = \sqrt{1 - \frac{1}{3}\left(1 + \frac{2k^2+4k}{2k^2+1}\right)} \\ \Delta q = 0 \end{cases} \tag{59}$$

From (57) and (59) for the following values are obtained:

$$\begin{cases} R_0 = 0 \\ R_p = 1 \\ R = 0 \end{cases} \qquad \text{No compensation is needed.}$$

These results are shown clearly in Fig. 10 and 11.

Case III: One phase unbalanced with nonlinear load. The following values are taken to calculate the different parameters used in the evaluation of the power ratio:

$$k_a = k_b = k_c = 1, \quad k'_a = k, \quad k'_c = k'_b = 1$$
$$\phi_a = \phi_b = \phi_c = 0, \quad \gamma_a = \gamma_b = \gamma_c = 0, \quad \sigma \succ 0.$$

The following figures give the values of the power ratio R of the Shunt APF, and the positive sequence apparent power ratio R_p. It is clear in Fig. 12 and 13 that the power

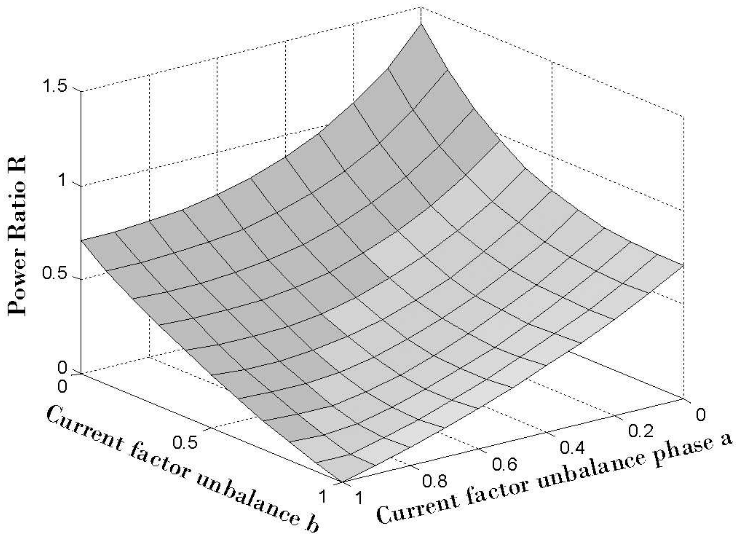

Figure 10. Power ratio when two phase unbalance current are occurred.

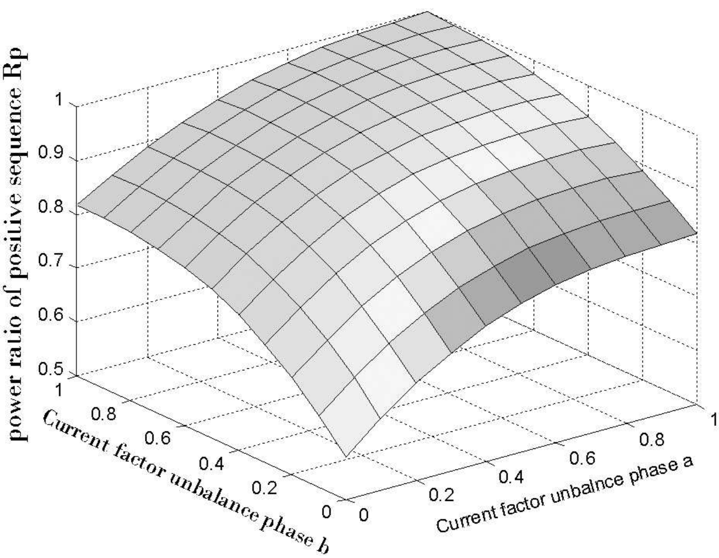

Figure 11. Power ratio of the positive sequence (two phases' currents unbalance).

ratios equal to 0 for $k = 1$ and $\sigma = 0$, this means no compensation is needed from the Shunt APF for balanced power system voltages and balanced linear load currents. This value is maximal when the current of phases is zero and σ equals to 1. In this case the power compensation needed from the Shunt APF is greater than the power produced

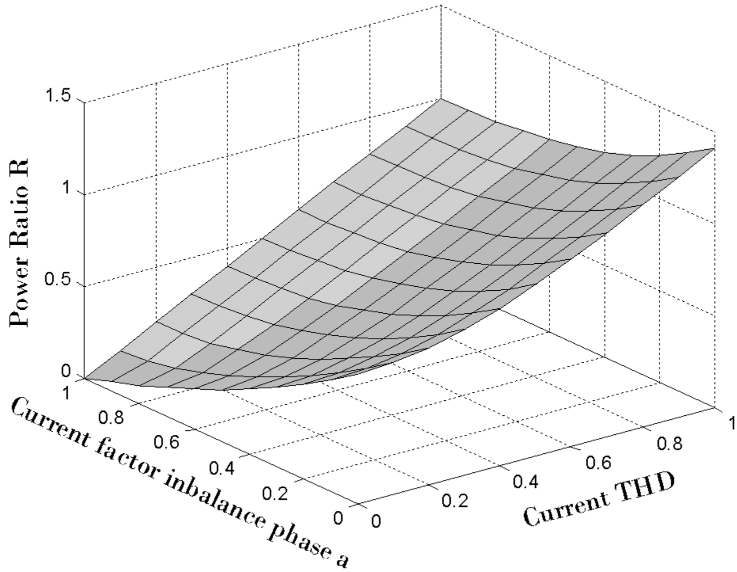

Figure 12. Power ratio when one phase distortion and unbalance are occurred.

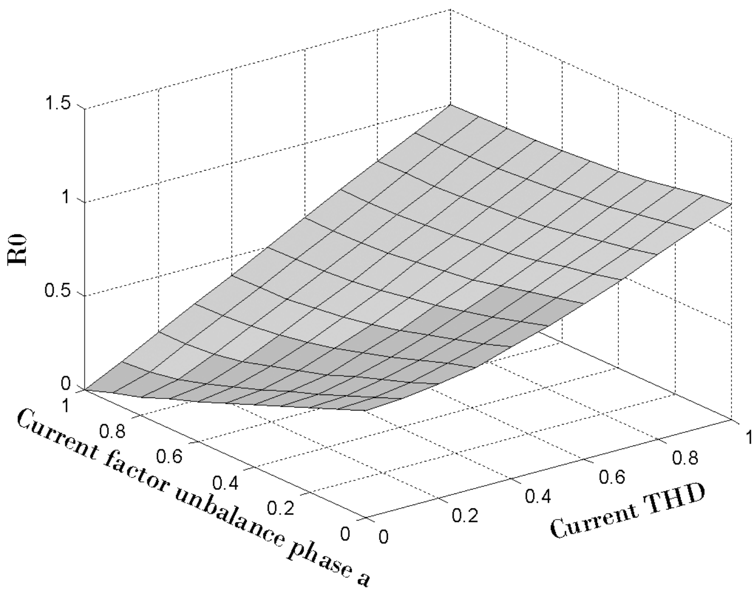

Figure 13. Power ratio R_0 when one phase distortion and unbalance are occurred.

by the power system to improve the quality of the currents circulating toward the power system to be balanced. It is clear that these results are given with nonlinear loads with the same high level harmonics distortion in the three phases, but such constraints are far from practical cases (where $\sigma < 1$) and leads the shunt APF to be useless. The same remark can be noticed for the positive sequence power ratio as in case I which is presented by:

$$R_p = \frac{1}{\sqrt{3}} \cdot \sqrt{1 + \frac{4k+2}{k^2+2}}. \tag{60}$$

R depends in this case only on R_p and R_0:

$$R = \frac{R_0}{R_p} \tag{61}$$

where:

$$\begin{cases} \Delta\beta = 1 \\ \gamma_1^+ = 0 \\ R_0 = \frac{1}{\sqrt{3}} \sqrt{2 + 3\sigma^2 - \frac{4k+2}{k^2+2}} \\ \Delta q = 0 \end{cases} \tag{62}$$

It follows from (62) that if $k = 1$ (balanced load currents) then:

$$\begin{cases} R_p = 1 \\ R = R_0 = \sigma \end{cases} \tag{63}$$

Hence, the compensating power needed is:

$$S_{comp} = \sigma \cdot S_s. \tag{64}$$

It depends on the quality of the nonlinear load. This presents the curve where the factor unbalance is equal to 1.

5. An optimal evaluation of the Shunt APF apparent power ratio

For a given characteristics of the load, the apparent power ratio can be evaluated using its constraints, furthermore, an optimal values can be obtained where R is the function to be maximized. Indeed, R depends on several variables presenting the parameters of the load and power system voltages. For the power system voltages the variables are:

$$\begin{cases} k_a, k_b, k_c \\ \phi_a, \phi_b, \phi_c \end{cases} \tag{65}$$

For the load the variables are:

$$\begin{cases} k'_a, k'_b, k'_c \\ \gamma_a, \gamma_b, \gamma_c \\ \sigma \end{cases} \tag{66}$$

To simplify the calculation these variables can be presented in the vector x defined by:

$$x = \begin{bmatrix} k_a & k_a & k_a & \phi_a & \phi_a & \phi_a & k'_a & k'_a & k'_a & \gamma_a & \gamma_a & \gamma_a & \sigma \end{bmatrix}'. \tag{67}$$

The objective function to be maximized is then:

$$R = f\left(k_a, k_b, k_c, \phi_a, \phi_b, \phi_c, k'_a, k'_b, k'_c, \gamma_a, \gamma_b, \gamma_c, \sigma\right). \tag{68}$$

Subject to the constraints:

$$A_c \cdot x \leqslant B_c. \tag{69}$$

The elements of the matrix are defined as:

$$A_{cij} = \begin{cases} +1 & \text{if} \quad i = 2 \cdot j - 1 \\ -1 & \text{if} \quad i = 2 \cdot j \end{cases} \qquad i = 1,2,3....2n \quad j = 1,2,3....n. \tag{70}$$

n represents the number of variables. i is the number of the row and j is the number of the column of the matrix A_c. Vector B_c represents the limits of the variables; it is expressed by:

$$B_c = \begin{bmatrix} B_{c1} \\ B_{c2} \end{bmatrix} \tag{71}$$

where:

$$\begin{aligned} B_{c1} &= \begin{bmatrix} 1 & k_{a\min} & 1 & k_{b\min} & 1 & k_{c\min} & 1 & k'_{a\min} & 1 & k'_{b\min} & 1 & k'_{c\min}, \end{bmatrix}' \\ B_{c2} &= [\phi_{a\max}, 0, \phi_{b\max}, 0, \phi_{c\max}, 0, \gamma_{a\max}, 0, \gamma_{b\max}, 0, \gamma_{c\max}, 0, \sigma_{\max}, 0]'. \end{aligned} \tag{72}$$

The main objective of the optimization problem presented in (68), (69) is to find $R_{\max}$. This ratio value corresponds to the optimal effective apparent power of the shunt APF which can fulfill the compensation requirement subject to the constraints given. This value is very useful in the process design, hence the over dimension of the shunt APF is avoided and the cost is minimized.

To solve this optimization problem, the Particle Swarm Optimization (PSO) is used, it is a population-based stochastic optimization algorithm modeled after the simulation of the social behavior of bird flocks, where the global optimization is investigated for finding the global minimum or maximum [40-52]. It is similar to genetic algorithms

(Gas) in the sense that both approaches are population-based and each individual has a objective function. Furthermore, the adjustments of the individuals in PSO are relatively similar to the arithmetic crossover operator used in GAs. However, PSO is influenced by the simulation of social behavior rather than the survival of the fittest. PSO is easy to be implemented as a software application with fast and cheap calculation, there is no need to derivatives, and starts with random starting initial solution and it converges to the global minimum or maximum. Indeed, it has been successfully applied to solve a wide range of optimization problems such as continuous nonlinear and discrete optimization problems in different field's applications [40-52]. In a PSO system, a swarm of individuals (called particles) fly through the search space. Each particle represents a candidate solution to the optimization problem. The position of a particle is influenced by the best position visited by itself (i.e. its own experience) and the position of the best particle in its neighborhood (i.e. the experience of neighboring particles), this means the search subspace in which the particles look for the best location. When the neighborhood of a particle is the entire swarm, the best position in the neighborhood is referred to as the global best particle, and the resulting algorithm is referred to as a global best position (*gbest*) PSO. When smaller neighborhoods are used, the algorithm is generally referred to as a local best position (*lbest*) PSO. The performance of each particle is measured using an objective function that varies depending on the optimization problem [40-52].

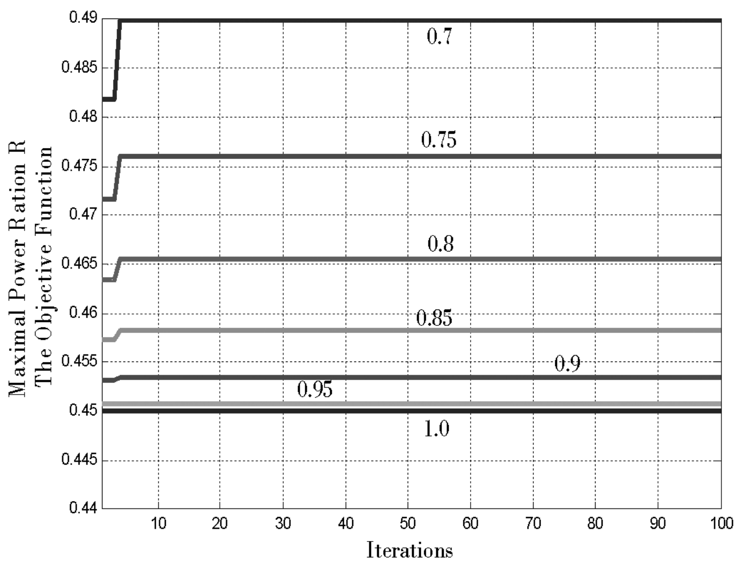

Figure 14. The objective function (maximal power ratio R) for different unbalance power system voltage factors under $THD = 0.45$.

Fig. 14 shows the maximal power ratio $R_{\max}$ found for different situations of the power system voltages magnitude unbalances under load distortion defined by $THD = 0.45$, where the voltage unbalance factors vary in the interval $[k_{i\min}\ 1]$, $i = a, b, c$. The

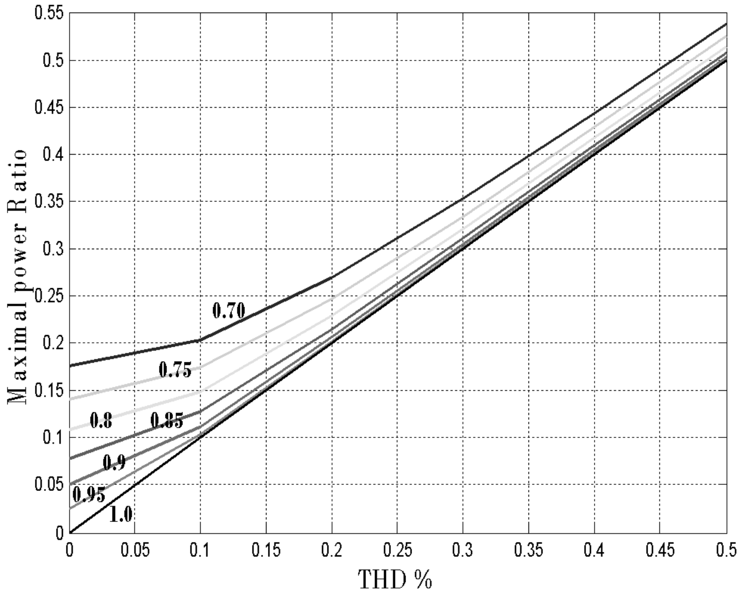

Figure 15. Maximal power ratio R versus THD for different unbalance factors of power system voltages.

objective function was tested for different values of $k_{i\min}$ (0.7, 0.75, 0.8, 0.85, 0.9, 0.95 and 1). This means that in each case the unbalance factors k_a, k_b and k_c vary in the interval $[k_{i\min}\ 1]$, but it is not obligatory to have the equality of the three factors, the maximal value of $R_{\max}$ corresponds to the worst case of power system voltage unbalance, where the maximal amount of apparent power compensation is needed. For $k_{i\min} = 0.8$, the power ratio $R_{\max} = 0.466$, this means that the maximal power of the SAPF is 46.6% of the power needed by the load, the rest of power 53.4% is delivered by the power source. While it is clear from Fig. 14, that for $k_{i\min} = 1$ the compensation apparent power needed is equal to 0.45% of the total apparent power needed by the load. On the other side it can be seen clearly that the convergence of the objective function towards the best solution is very rapid, it is achieved in a few iterations, less then 5 iterations for all the cases. In Fig. 15, Fig. 16 and Fig. 17 the maximal power ratio R_{max} is found for different unbalances situations versus THD which varies within the limits of $[0\ 0.5]$.

Fig. 15 presents the maximal power ratio R for different values of $k_{i\min}$ (0.7,0.75,0.8,0.85,0.9,0.95 and 1) versus a varied THD, it is clear that for $k_{i\min} = 1$, the curve of $R_{\max}$ is a linear function passes by (0, 0) and (0.5, 0.5), in this case the value of the maximal power ratio $R_{\max}$ remains equal to THD as it is proved in (64). On the other side, the maximal value of THD for different values of $K_{i\min}$ which corresponds to the Shunt APF apparent power to be equal to 50% of the apparent power absorbed by the load can be extracted from Fig. 15. These values are presented in Tab. 1.

Table 2. The maximal $THD_{\max}$ corresponding to $R_{\max} = 0.5$ versus $k_{i\min}$

$k_{i\min}$	0.70	0.75	0.80	0.85	0.90	0.95	1.00
$THD_{\max}$	0.4600	0.4747	0.4850	0.4922	0.4968	0.4993	0.5000

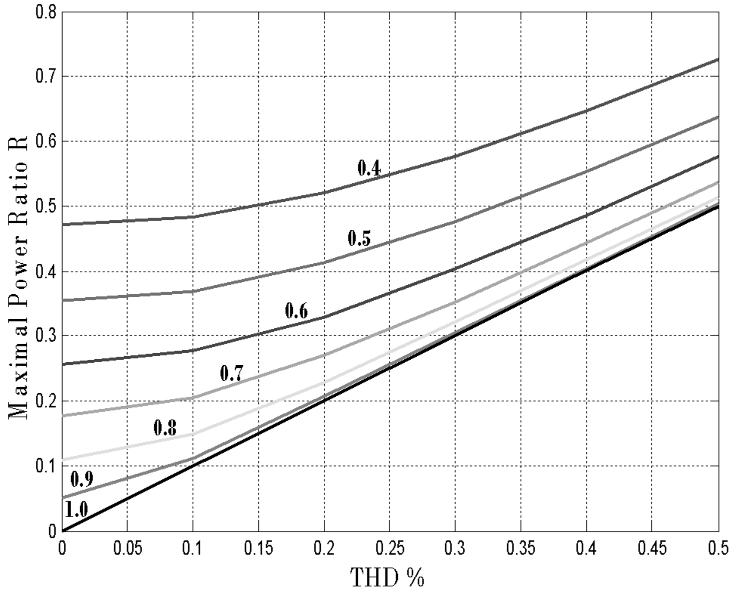

Figure 16. Maximal power ratio R versus THD for different unbalance factors of the load currents.

Table 3. The maximal $THD_{\max}$ corresponding to $R_{\max} = 0.5$ versus $k_{i\min}$

$k_{i\min}$	0.40	0.50	0.60	0.70	0.80	0.90	1.00
$THD_{\max}$	0.1433	0.3318	0.4150	0.4600	0.4850	0.4968	0.5000

Fig. 16 presents the maximal power ratio $R_{\max}$ for different values of $k'_{i\min}$ (0.4,0.5,0.6,0.7,0.8,0.9 and 1) versus a varied THD, where $k'_{i\min} = k'_{a\min}$, $k'_{b\min}$, $k'_{c\min}$ are the minimum limits of the load unbalances factors of the three phases. It is supposed in this case that the power system voltages are balanced $k_a = k_b = k + c = 1$. It is obvious that for $k'_{i\min} = 1$, the curve of $R_{\max}$ is a linear function passes by (0, 0) and (0.5, 0.5), in this case the value of the maximal power ratio $R_{\max}$ remains equal to THD, it is the same as in Fig. 15. On the other hand, the maximal value of THD for different values of $k_{j\min'}$ which corresponds to the Shunt APF apparent power to be equal to 50% of the apparent power absorbed by the load are presented in Tab. 2.

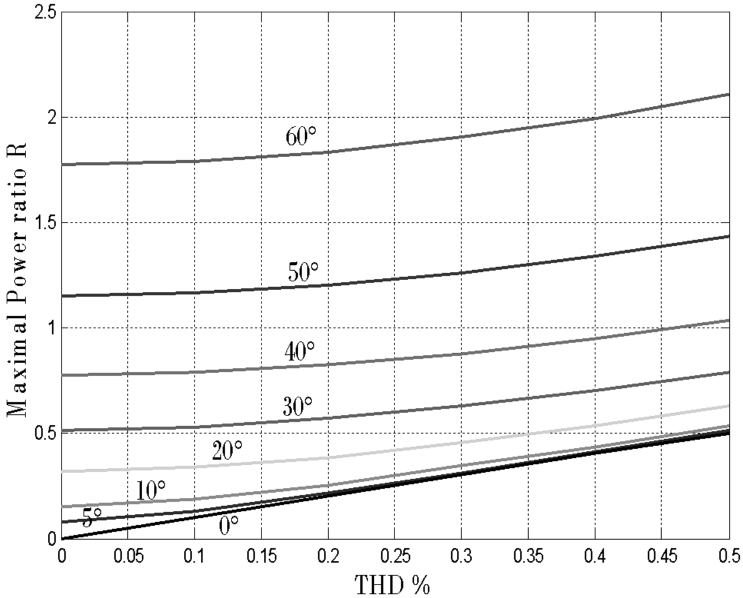

Figure 17. Maximal power ratio R versus THD for different phase shift phase and phase shift phase unbalances in the load currents.

Table 4. The maximal $THD_{\max}$ corresponding to $R_{\max} = 0.5$ versus $k_{i\min}$

$k_{i\min}$	60^{o}	50^{o}	40^{o}	30^{o}	20^{o}	10^{o}	5^{o}	0^{o}
$THD_{\max}$	0.0	0.0	0.0	0.0	0.3582	0.4677	0.4921	0.5

Fig. 17 presents the maximal power ratio $R_{\max}$ for different values of $\gamma_{i\max}$ $(5^{o}, 10^{o}, 20^{o}, 30^{o}, 4^{o}, 50^{o}$ and $60^{o})$ versus a varied THD, where $\gamma_{i\max} = \gamma_{a\max}, \gamma_{b\max}, \gamma_{c\max}$ present the maximum limits of the load unbalances phases shift of the three phases. It is supposed in this case that the power system voltages are balanced $k_a = k_b = k_c = 1$ and the magnitude load currents are equal in the three phases $k'_a = k'_b = k'_c = 1$. It is obvious that for $\gamma_{i\max} = 0^{o}$, the curve of $R_{\max}$ is a linear function passes by (0, 0) and (0.5, 0.5), in this case the value of the maximal power ratio R_{max} remains equal to THD, it is the same as in Fig. 15 and Fig. 16. On the other hand, the maximal value of THD for different values of $\gamma_{i\max}$ which corresponds to the Shunt APF apparent power to be equal to 50% of the apparent power absorbed by the load are presented in Tab. 3.

It can be noticed from Tab. 3, that to ensure the compensation by the Shunt APF, the apparent power delivered to the load is more than 50% of the load apparent power for $\gamma_{i\max} \geqslant 29.451^{o}$. This means that the use of the Shunt APF is more expensive.

Tab. 4 presents general situation of voltage unbalance, where the maximal voltage unbalance is 30%, which corresponds to $k_{\max} = 0.7$, the maximal phase shift unbalance is $\gamma_{\max} = \pi/2$. The results of the optimized value of the power ratio according to the problem presented in (68), subject to (69) for $THD \in [0,\ 0.7]$ are presented in Fig. 18. It is shown clearly that $R_{\max} \leqslant 0.73$ corresponds to the case of magnitude unbalances of one phase, two phases and three phases respectively, while the phase shift of different phases are kept equal to zero. On the other side $R_{\max} \geqslant 0.75$ corresponds to the case of magnitude and phase shift unbalances in one phase, two phases or three phases, as they are presented in Tab. 4.

Tab. 5 presents the same cases as in Tab. 4, but for the load current unbalances following from the magnitudes and phases shift. The curves in Fig. 19 present the results of the problem presented in (68) subject to (69) for $THD \in [0,\ 0.7]$, where (69) is defined according to the unbalances found in Tab. 5. The large value of the power ratio are shown clearly in Fig. 19. Of course, these values present the maximal power ratio subject to the constraints of the unbalances in the load currents. For example, it follows from Fig. 19 that for unbalanced current load in one phase of 40% without current distortion, the power compensation needed by the Shunt APF is 20% of the apparent power needed by the load. Under the same conditions with $THD = 0.3$, the apparent power of compensation is 35% of the apparent power required by the load.

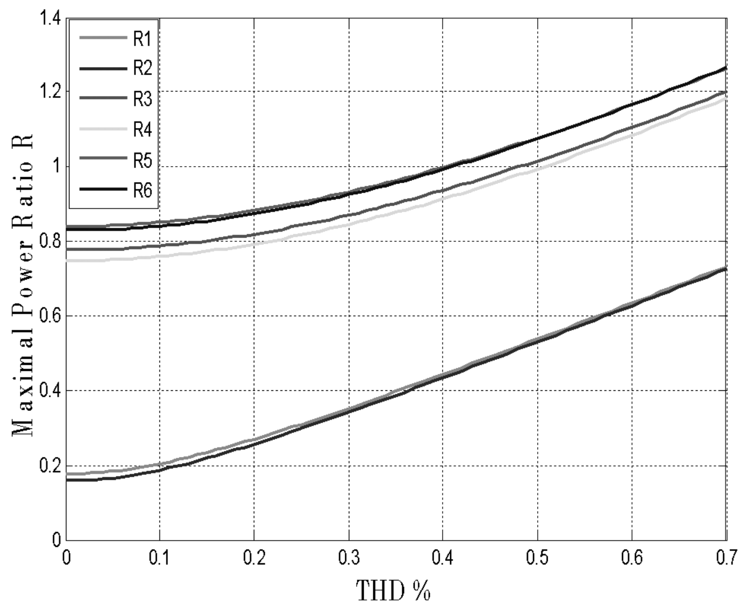

Figure 18. Maximal power ratio R versus load THD for different unbalances of power system voltages.

Table 5. Limits of the constraints in the case of power system voltage unbalances

	k_a min	k_b min	k_c min	ϕ_a min	ϕ_b min	ϕ_c min
R_1	1	1	0.7	0	0	0
R_1	0.7	0.7	0.7	0	0	0
R_2	0.7	0.7	1	0	0	0
R_3	1	1	1	$\pi/3$	0	0
R_3	1	1	1	$\pi/3$	$\pi/3$	0
R_3	0.7	1	1	$\pi/3$	0	0
R_4	1	1	1	$\pi/3$	$\pi/3$	$\pi/3$
R_5	0.7	0.7	1	$\pi/3$	$\pi/3$	0
R_6	0.7	0.7	0.7	$\pi/3$	$\pi/3$	$\pi/3$

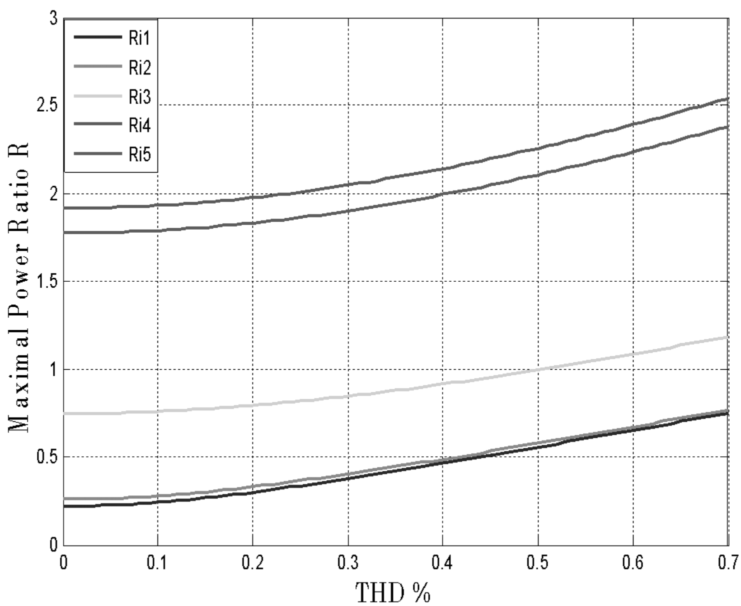

Figure 19. Maximal power ratio R versus load THD for different load currents unbalances.

6. Conclusion

This paper deals with the evaluation of the Shunt APF apparent power ratio for different current/voltage unbalances compensations. The evaluation of this value contributes directly in the process design optimization for the determination of the used devices

Table 6. Limits of the constraints in the case of the load currents unbalances

	k'_a min	k'_b min	k'_c min	ϕ_a max	ϕ_b max	ϕ_c max
R_{i1}	1	1	0.6	0	0	0
R_{i2}	0.6	0.6	0.6	0	0	0
R_{i2}	0.6	0.6	1	0	0	0
R_{i3}	1	1	1	$\pi/3$	0	0
R_{i3}	0.6	1	1	$\pi/3$	0	0
R_{i4}	0.6	0.6	1	$\pi/3$	$\pi/3$	0
R_{i4}	0.6	0.6	0.6	$\pi/3$	$\pi/3$	$\pi/3$
R_{i5}	1	1	1	$\pi/3$	$\pi/3$	0
R_{i5}	1	1	1	$\pi/3$	$\pi/3$	$\pi/3$

dimensions. The calculated apparent power defines the needed compensating apparent power subject to special loads or special consumer's needs, where the consumer's equipments are well known previously. The objective of this optimization calculation is to avoid over or/and under dimensions evaluations of the Shunt APF. This is important for the manufacturers and users to minimize economically the burdens of production and the use of such equipments. On the other side, this study is based on new definition of the apparent power, which is proved to be the suitable amount to be considered in the process design, it shows the errors which were made for the evaluation of the apparent power to dimension these equipments using the classical definitions, where these definitions are correct only for sinusoidal balanced systems of voltages and currents. It is important to clarify that the evaluation of the apparent power of the Shunt APF needed by the users is determined by the constraints of the loads to be fed and also by the constraints of the power system source. The approach given in this paper can achieve this aim.

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