XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

WHY REACTIVE COMPENSATORS DO NOT IMPROVE THE EFFICIENCY CORRECTLY IN UNBALANCED CIRCUITS

V. León-Martínez[1], *J. Montañana-Romeu*[1], *J. Roger-Folch*[1], *A. Cazorla Navarro*[1]
[1] Universidad Politécnica de Valencia, Valencia, Spain, vleon@die.upv.es

Abstract − This paper shows utility of phasor total unbalance power as a tool to explain working of unbalanced power systems. Conditions under shunt capacitors used to compensate reactive power can deteriorate the efficiency in three-phase four-wire unbalanced at loads power systems are described. Reactive phenomenon is studied using Emanuel´s positive-sequence fundamental-frequency reactive power, included in the IEEE Standard 1459-2000. Unbalance phenomenon is analyzed using the phasor total unbalance power. This quantity measures unbalance power due to the active loads by separating of those caused by the reactive loads. Results of this analysis show that reactive phenomenon in three-phase power systems can be compensated by single or three-phase capacitor banks, but undesirable effects on the system efficiency are consequence of the unbalance phenomenon and they can be increased by an inadequate reactive-compensator topology. It can have unbalance power due to the reactive loads even thought the reactive power has been compensated.

Keywords: Compensation, industrial power systems, power capacitors, power factor, power measurement, reactive power.

1. INTRODUCTION

Presence of power capacitor banks for reactive power compensation is very frequent at industrial electric installations for a long time. The most common compensator topology for industrial power systems is three-phase balanced capacitors, but single-phase capacitors used for compensating single-phase loads are placed in three-phase electrical networks too.

When three-phase balanced capacitor banks are working in unbalanced power systems some phases of the excitation sources can become capacitive. This inadequate working is very dangerous when it takes place near power transformers because it can originate Ferranti’s over-voltages, which can deteriorate those electrical machines, causing failures in the loads and their destruction, in some occasions. If these over-voltages do not occur, it is always observed that efficiency, defined by the power factor, of those power systems is improved by the connection of three-phase balanced capacitor banks. However, when single-phase capacitor banks are placed in three-phase power systems, practical experiences show efficiency improvement can be less than it could be expected and the efficiency can even decrease in some power systems, being increased the line currents and power losses.

The question is now: why the efficiency is deteriorated in these last power systems and which phenomenon is the most responsible on the reduction of the power factor. For answering that question, in this paper, each involved phenomena, reactive and unbalance, are analyzed for three-phase power systems supplied with balanced voltages. Fundamental-frequency positive-sequence reactive power [1]-[4], [10], [11], included in the IEEE Standard 1459-2000 [12], is used to define reactive effects, while phasor total unbalance power [9], [10], [13] is used for measuring unbalance power effects. This complex quantity holds two components; real component defines unbalance effects due to the active loads and imaginary component of phasor total unbalance power measures unbalance effects caused by the reactive loads. However, as active loads are not modified by the connection of compensating capacitors, for the present study, only unbalance power caused by the reactive loads are measured.

Analysis made in this paper by applying the two above indicated quantities for unbalanced three-phase power systems supplied with symmetrical voltages demonstrates that topology of shunt capacitors does not change the reactive phenomenon in power systems. Shunt capacitors compensate the same reactive power independently of their physical disposition in the power system, but unbalance phenomenon can be strongly modified, increasing or decreasing values of unbalance power depending on the topology of the reactive compensating devices. It is verified that when balanced three-phase compensators are used, the system efficiency is improved, since reactive power is reduced and unbalance phenomenon is not modified. However, when single or unbalanced three-phase capacitors banks are used, values of unbalance power can be modified. Whether these last compensating devices are placed adequately, both reactive and unbalance powers decrease and the efficiency improvement is rather than with the use of balanced compensating devices, but when three-phase unbalanced capacitor banks are not placed correctly in the system, unbalance power is increased, although reactive power is reduced. Unbalance power changes are yield by the reactive loads, since unbalance caused by the active loads is not modified by the connection of power capacitors.

2. POWERS IN THREE-PHASE SINUSOIDAL BALANCED AT SUPPLIES POWER SYSTEMS.

Let us consider a three-phase four-wire sinusoidal unbalanced at loads power system with negligible neutral impedance and balanced supply voltages of positive-sequence ($\overline{V}_z = \overline{V}_{+z}$), where subscript z = 1,2,3 denotes the phases of the power system. Phase currents can be decomposed, by Fortescue [5], into positive (+), negative (-) and zero (0) sequence components expressed in CMRS values:

$$\overline{I}_z = \overline{I}_{+z} + \overline{I}_{-z} + \overline{I}_{0z} \quad (1)$$

Also, these currents can be associated to three distinctive phenomena: active, reactive and unbalance currents.

Active currents ($\overline{I}_{az}$) are the components of the positive-sequence currents in phase with the positive-sequence voltages in each phase (z) of the power system:

$$\overline{I}_{az} = \overline{I}_{a+z} = G_+ \cdot \overline{V}_{+z} \quad (2)$$

being $G_+ = P / 3V_+^2$ the positive conductance of the load. Active currents transfer active power (P) to the load:

$$P = \sum_{z=1}^{3} V_{+z} \cdot I_{a+z} = 3V_+ \cdot I_a \quad (3)$$

Reactive currents ($\overline{I}_{rz}$) are the components of positive-sequence current which are phase-shift 90 degrees with respect to the positive-sequence voltages:

$$\overline{I}_{rz} = \overline{I}_{r+z} = \overline{B}_+ \cdot \overline{V}_{+z} \quad (4)$$

where $\overline{B}_+ = Q / 3V_+^2$ is the positive susceptance of the load. Reactive current exists due to the phase-shift between positive-sequence voltages and currents. Reactive power (Q) defines effects of that phenomenon:

$$Q = \sum_{z=1}^{3} V_{+z} \cdot I_{r+z} = 3V_+ \cdot I_r \quad (5)$$

Active and reactive powers expressed by (3) and (5), respectively, are Emanuel's fundamental-frequency positive-sequence active and reactive powers [2] included in the IEEE Standard 1459-2000 [12].

Unbalance currents ($\overline{I}_{uz}$)

$$\overline{I}_{uz} = \overline{I}_z - \overline{I}_{az} - \overline{I}_{rz} = \overline{I}_{-z} + \overline{I}_{0z} \quad (6)$$

are caused by the unbalances at loads; they are negative and zero sequence currents. Unbalance currents transfer unbalance power:

$$A_U = 3V_+ \sqrt{I_-^2 + I_0^2} \quad (7)$$

Unbalance power obtained with the above expression gives up the same values which those resulting of Czarnecki's unbalanced power [6]-[8] for balanced voltage conditions:

$$S_U = \sqrt{3V_+^2 \cdot (I_{u1}^2 + I_{u2}^2 + I_{u3}^2)} \quad (8)$$

In this paper, unbalance power expressed by (7) or (8) will be used since we want to study reactive and unbalance phenomena caused by the loads.

However, unbalance power (A_U) is not a conservative quantity and hence total unbalance power of several loads is not generally the arithmetic sum of their unbalance powers. Also, unbalance power give up a little information about the unbalance phenomenon, since this quantity only indicates the magnitude of the unbalance phenomenon effects. All these objections of the unbalance power for studying the unbalance phenomenon can be avoided by using the phasor total unbalance power [9]. This quantity is expressed in the following section.

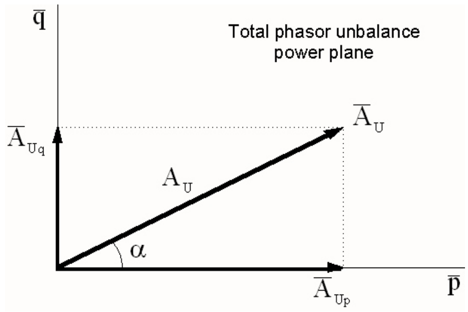


Fig. 1. Total phasor unbalance power and their components.

3. PHASOR TOTAL UNBALANCE POWER.

Phasor total unbalance power ($\overline{A}_U$) is a complex quantity whose module is the unbalance power (A_U) expressed by (7) and so it measures the unbalance effects caused by the load. This quantity has two components ($\overline{A}_{Up}$, $\overline{A}_{Uq}$) defined on two orthogonal axis characterized by the unitary phasors $\overline{p} = e^{j0^o}$, $\overline{q} = e^{j90^o}$ (Fig. 1).

$$\overline{A}_U = A_{U\,|\,\alpha} = \overline{A}_{Up} + \overline{A}_{Uq} \quad (9)$$

Component $\overline{A}_{Up}$ of phasor total unbalance power measures the unbalance phenomenon caused by the active loads. Expression of this component in function of the active powers of each load phase (P_1, P_2, P_3) is the following, such as it was demonstrated in [9]:

$$\overline{A}_{Up} = \left|\overline{A}_{up}\right| \cdot \overline{p} = \left|\sqrt{2}\,(P_1 + a^2 P_2 + a\,P_3)\right| \cdot \overline{p} \quad (10)$$

where $a = e^{j120^o}$ and between bars is expressed the module of a complex quantity

$$\overline{A}_{up} = A_{up}\, e^{j\alpha_p} = \sqrt{2}\,(P_1 + a^2 P_2 + a\,P_3) \quad (11)$$

whose angle α_p indicates the phase or phases most unbalanced of the active loads.

Component $\overline{A}_{Uq}$ of phasor total unbalance power measures the unbalance phenomenon yield by the reactive loads. Its expression in function of the complex reactive powers of each phase of the load ($\overline{Q}_1, \overline{Q}_2, \overline{Q}_3$) is, such as it was seen in [9]:

$$\overline{A}_{Uq} = \left|\overline{A}_{uq}\right| \cdot \overline{q} = \sqrt{2} \left| \overline{Q}_1 + a^2 \overline{Q}_2 + a\, \overline{Q}_3 \right| \cdot \overline{q} \qquad (12)$$

where

$$\overline{A}_{uq} = A_{uq}\, e^{j\alpha_q} = \sqrt{2} \cdot (\overline{Q}_1 + a^2 \overline{Q}_2 + a\, \overline{Q}_3) \qquad (13)$$

is a complex quantity whose angle (α_q) indicates the phase or phases most unbalanced of the reactive loads.

General expression of phasor total unbalance power is, in function of the active (P_z) and complex reactive ($\overline{Q}_z$) powers of the system phases (z = 1,2,3):

$$\overline{A}_U = \sqrt{2} \left(\overline{p} \cdot \left| P_1 + a^2 P_2 + a\, P_3 \right| \pm \overline{q} \cdot \left| \overline{Q}_1 + a^2 \overline{Q}_2 + a\, \overline{Q}_3 \right| \right) \quad (14)$$

being the positive sign for inductive loads and the negative sign for capacitive loads.

Phasor total unbalance power can be also expressed in function of the conductances (G_z) and conjugate susceptances ($\overline{B}_z^*$) of the load phases:

$$\overline{A}_U = \sqrt{2}\, V^2 \left(\overline{p} \cdot \left| G_1 + a^2 G_2 + a\, G_3 \right| \pm \overline{q} \cdot \left| \overline{B}_1^* + a^2 \overline{B}_2^* + a\, \overline{B}_3^* \right| \right) \quad (15)$$

where the signs (+,-) have the signification indicates above and Re and Im are the real and imaginary parts of the complex power of each load phase.

All the above expressions of phasor total unbalance power are based on the consideration of active and reactive powers delivery in each phase of the power system is 120º shifted with respect to the active and reactive powers in the other two system phases in the own space of the unbalance phenomenon. In our opinion, these expressions can be also applied to three-phase sinusoidal or non-sinusoidal power systems with balanced voltages and with both sources and loads in star or delta connections.

Phasor total unbalance power has the following properties:

- Phasor total unbalance power ($\overline{A}_U$) is zero when the loads are balanced.
- Phasor total unbalance power ($\overline{A}_U$) of a three-phase power system is the complex sum of the phasor total unbalance power of each of their loads or integrating parts.

4. REACTIVE COMPENSATED POWER SYSTEMS.

Reactive and unbalance phenomena are analyzed in this section for sinusoidal three-phase unbalanced at loads power systems compensated with power capacitors with different topologies. SIMPELEC evaluation software [13], [14] based on LabVIEW is used for this study.

Let us consider the sinusoidal, three-phase unbalanced at loads circuit, showed in Fig. 2, supplied with 230 V line to neutral, sinusoidal, symmetrical, positive-sequence RMS-voltages, with the following power consumptions in each phase: $P_1 = 10.58\ kW;\ P_2 = 26.45\ kW;\ Q_3 = 13.225\ kVAr$.

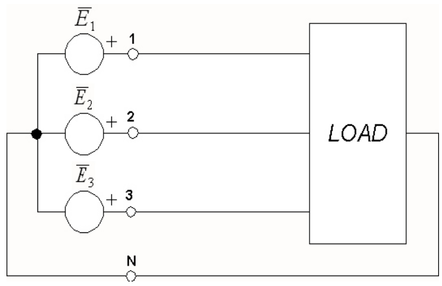


Fig. 2. Three-phase, sinusoidal, unbalanced at loads circuit.

Phase voltages have the following values:

$$\overline{E}_1 = 230 \cdot e^{j0^o} \quad \overline{E}_2 = 230 \cdot e^{-j120^o} \quad \overline{E}_3 = 230 \cdot e^{j120^o} \qquad (16)$$

And the line currents are:

$$\overline{I}_1 = 46 \cdot e^{j0^o} \quad \overline{I}_2 = 115 \cdot e^{-j120^o} \quad \overline{I}_3 = 57.5 \cdot e^{j30^o} \qquad (17)$$

Symmetrical components of those currents are, by Fortescue [5]:

$$\begin{aligned} \overline{I}_+ &= \tfrac{1}{3}(\overline{I}_1 + a\, \overline{I}_2 + a^2 \overline{I}_3) = 56.97 \cdot e^{-j19.63^o} \\ \overline{I}_- &= \tfrac{1}{3}(\overline{I}_1 + a^2 \overline{I}_2 + a\, \overline{I}_3) = 47.38 \cdot e^{-j244.5^o} \\ \overline{I}_0 &= \tfrac{1}{3}(\overline{I}_1 + \overline{I}_2 + \overline{I}_3) = 26.84 \cdot e^{-j61.2^o} \end{aligned} \qquad (18)$$

Positive-sequence currents hold two components: active and reactive. Active currents of the three-phase system are, from (18):

$$\overline{I}_{a1} = 53.59 \cdot e^{j0^o} \quad \overline{I}_{a2} = 53.59 \cdot e^{-j120^o} \quad \overline{I}_{a3} = 53.59 \cdot e^{j120^o} \qquad (19)$$

Reactive currents of the three-phase system are, from (18):

$$\overline{I}_{r1} = 19.09 \cdot e^{-j90^o} \quad \overline{I}_{r2} = 19.09 \cdot e^{-j210^o} \quad \overline{I}_{r3} = 19.09 \cdot e^{j30^o} \qquad (20)$$

and the unbalance currents, by (6):

$$\begin{aligned} \overline{I}_{u1} &= \overline{I}_1 - \overline{I}_{a1} - \overline{I}_{r1} = 20.7 \cdot e^{-j111.61^o} \\ \overline{I}_{u2} &= \overline{I}_2 - \overline{I}_{a2} - \overline{I}_{r2} = 64.26 \cdot e^{-j102.6^o} \\ \overline{I}_{u3} &= \overline{I}_3 - \overline{I}_{a3} - \overline{I}_{r3} = 65.94 \cdot e^{-j24.65^o} \end{aligned} \qquad (21)$$

Active and reactive powers obtained with (3) and (5), respectively, are:

$$P = 37.03\ kW \qquad Q = 13.225\ kVAr \qquad (22)$$

(the same values are obtained by Boucherot) and the unbalance power, by (7) or (8):

$$S_U = A_U = 37.56\ kVAa \qquad (23)$$

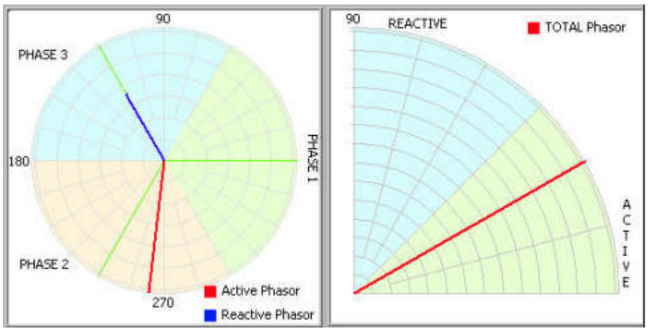
This quantity expresses the magnitude of the unbalance effects, but it does not inform about how this unbalance occurs, since there are unbalances caused by the active and reactive loads in the circuit of Fig. 2 whose effects are not expressed by (23). It is necessary to use phasor total unbalance power for obtaining more information about the unbalance phenomenon. Phasor total unbalance power is:

$$\overline{A}_{U\,load} = 37.56 \cdot e^{j29.84^o} = 23.58\,\overline{p} + 18.69\,\overline{q} \quad kVAa \qquad (24)$$

Figure 3, obtained from SIMPELEC simulation software [14], shows phasor unbalance power and their components. Unbalance caused by the active loads is represented by the red-line and unbalance due to the reactive loads is showed by the blue-line in Fig. 3a. $\overline{A}_{up}$ and $\overline{A}_{uq}$ components of phasor unbalance power, obtained from (11) and (13), respectively, are represented by these lines:

$$\overline{A}_{up} = 23.58 \cdot e^{-j96.59^o} \; kVAa \quad \overline{A}_{uq} = 18.69 \cdot e^{j120^o} \; kVAa \quad (25)$$

It is appreciated from that figure unbalance caused by the active loads is greater than the unbalance due to the reactive loads (this one can be also appreciated in Fig 3b), since red line is bigger than blue line. Fig. 3a also shows phase 2 of the load is the main responsible of unbalance due to the active loads (α_p = -96.59º), while unbalance caused by the reactive loads is only yield by phase 3 (α_q = 120º). Fig. 3b shows angle of phasor total unbalance power, which indicates importance of active and reactive loads in the unbalance phenomenon. When red-line is on 0º, unbalance is caused by the active loads. When red-line is on 90º, unbalance is due to the reactive loads. In the present application example, angle of phasor total unbalance power is 29.84º, how it can be appreciated in (24), and thus unbalance effects caused by the active loads are greater than those due to the reactive loads.



a) b)

Fig. 3. Phasor total unbalance power: a) active and reactive components importance in the phases, b) angle of phasor total.

Two reactive compensators can be used for efficiency improvement in the circuit of Fig. 2: three- and single-phase capacitor banks.

4.1. Three-phase balanced capacitor bank.

This is the most traditionally used compensator in industrial utilities. Figure 4 shows the unbalanced at loads circuit of the Fig.2 compensated by a three-phase balanced star-connected power capacitor. Total compensation is obtained when capacitor bank power is equal to the reactive power of the load ($Q_c = 13.225\;kVAr,\; C = 265.25\;\mu F$).

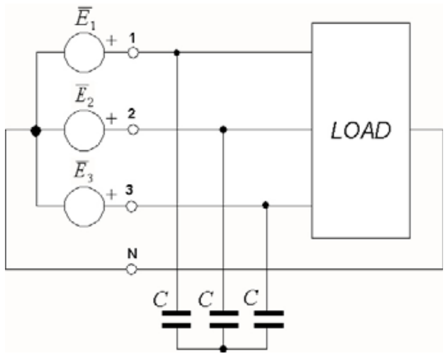


Fig. 4. Unbalanced at loads circuit compensated by thee-phase balanced capacitor bank.

Line currents supplied by the generator after compensating are the following:

$$\overline{I}_1' = 49.82 \cdot e^{j22.61^o}\,(A) \quad \overline{I}_2' = 116.59 \cdot e^{-j110.64^o}\,(A) \quad \overline{I}_3' = 38.34 \cdot e^{j30^o}\,(A) \qquad (26)$$

Those line currents are unbalanced. Positive-sequence currents in the circuit of Fig. 4 only have active component:

$$\overline{I}_+' = \tfrac{1}{3}(\overline{I}_1' + a\,\overline{I}_2' + a^2\,\overline{I}_3') = 53.59 \cdot e^{j0^o} = \overline{I}_a' \qquad (27)$$

Active currents are not modified by the connection of the capacitor bank, but now generator does not supply reactive currents, since they have been fully compensated.

Unbalance currents:

$$\begin{aligned} \overline{I}_{u1}' &= \overline{I}_1' - \overline{I}_{+1}' = 20.7 \cdot e^{-j111{,}61^o} \\ \overline{I}_{u2}' &= \overline{I}_2' - \overline{I}_{+2}' = 64.26 \cdot e^{-j102{,}6^o} \\ \overline{I}_{u3}' &= \overline{I}_3' - \overline{I}_{+3}' = 65.94 \cdot e^{-j24{,}65^o} \end{aligned} \qquad (28)$$

are not modified by the connection of the capacitor bank. Active power supplied by the generator is the same in both circuits compensated and non-compensated, but reactive power supplied by the generator is zero after compensation:

$$P' = 37.03\;kW \qquad Q' = 0 \qquad (29)$$

and the phasor total unbalance power can be obtained adding the phasor total unbalance power of the compensator, obtained by (15), and the phasor total unbalance power of the load, expressed by (24), where the negative sign is due to the capacitive character of the compensator:

$$\begin{aligned} \overline{A}_U' &= \overline{A}_{Ucompensator} + \overline{A}_{U\,load} = \\ &= -\sqrt{2} \cdot 230^2 \cdot \left(\left| \frac{Q_c}{3} + \frac{Q_c}{3} a^2 + \frac{Q_c}{3} a \right| \right) \overline{q} + \overline{A}_{U\,load} = \\ &= \overline{A}_{U\,load} = 37.56 \cdot e^{j29{,}84^o}\;(kVAa) \end{aligned} \qquad (30)$$

It is observed active and unbalance phenomena are not modified by the connection of a balanced capacitor bank, since this is a reactive balanced load, thus value of phasor total unbalance power is not changed and its representation is the same showed in Fig. 3. However, delivery of reactive power and currents from the sources has been eliminated and the efficiency has been improved.

4.2. Single- phase capacitor bank.

This procedure of compensation is very usual when there are single-phase reactive loads connected to three-phase networks. Figure 5 shows one capacitor (C_s) to compensate reactive power in the unbalance circuit of Fig. 2, but this is not placed in the same phase where the reactive load is. Power and capacity of that capacitor for total reactive compensation are: $Q_c = 13.225\ kVAr,\ C_s = 795.75\ \mu F$.

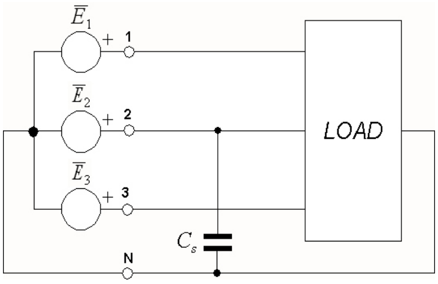


Fig. 5. Unbalanced at loads, compensated by single-phase capacitor bank circuit.

Line currents supplied by the generator are now:

$$\overline{I}_1'' = 46 \cdot e^{j0^o}\,(A) \quad \overline{I}_2'' = 128.57 \cdot e^{-j95{,}44^o}\,(A) \quad \overline{I}_3'' = 57.5 \cdot e^{j30^o}\,(A) \tag{31}$$

Positive-sequence component of those line currents are:

$$\overline{I}_+'' = \tfrac{1}{3}(\overline{I}_1'' + a\,\overline{I}_2'' + a^2\,\overline{I}_3'') = 53{,}59 \cdot e^{j0^o} = \overline{I}_a'' \tag{32}$$

There is no reactive current. And unbalance currents have changed:

$$\begin{aligned} \overline{I}_{u1}'' &= \overline{I}_1'' - \overline{I}_{+1}'' = 7.59 \cdot e^{-j180^o}\ (A) \\ \overline{I}_{u2}'' &= \overline{I}_2'' - \overline{I}_{+2}'' = 82.8 \cdot e^{-j79{,}85^o}\ (A) \\ \overline{I}_{u3}'' &= \overline{I}_3'' - \overline{I}_{+3}'' = 55.59 \cdot e^{-j133^o}\ (A) \end{aligned} \tag{33}$$

Active and reactive powers are, from (3) and (5):

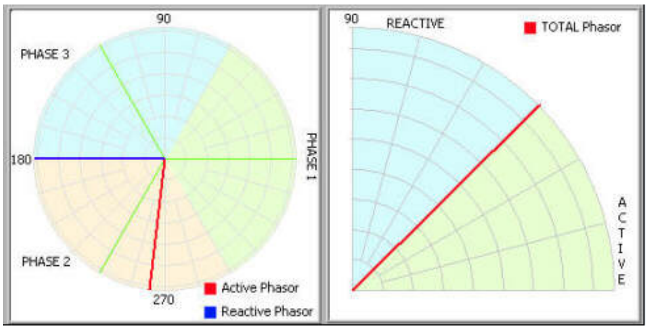
$$P'' = 37.03\ kW \qquad Q'' = 0 \tag{34}$$

Total phasor unbalance power is obtained by the complex sum of phasor unbalance powers of the capacitor and load and the negative sign is due to the capacitive reactive power of the capacitor:

$$\begin{aligned} \overline{A}_U'' &= \overline{A}_{Ucapacitor} + \overline{A}_{U\,load} = \\ &= -\sqrt{2} \cdot 230^2 \cdot \left(\left| \overline{Q}_c \cdot a^2 \right| \right) \overline{q} + \overline{A}_{U\,load} = 45.97 \cdot e^{j44{,}8^o}\,(kVAa) \end{aligned} \tag{35}$$

It is observed reactive power and currents supplied by the generator are eliminated in spite of the capacitor is connected to a different phase where the reactive load is.

Active power is not modified, but unbalance power has been increased by the connection of the capacitor. From (35), it is verified that increase of the unbalance phenomena is due to the reactive loads, since angle of phasor total unbalance power has been increased from 29,84º, without



a) b)

Fig. 6. Phasor total unbalance power: a) active and reactive components importance in the phases, b) angle of phasor total.

capacitor, up to 44,8º (Fig. 6b), when the capacitor is connected. Unbalance power due to the active loads is not modified by the capacitor connection and unbalance due to the reactive loads is now due to the phases 2 and 3 (Fig. 6a).

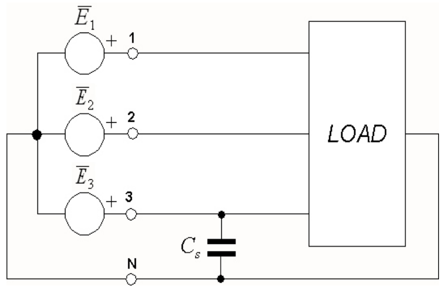


Fig. 7. Unbalanced at loads, compensated by single-phase capacitor bank circuit.

When capacitor C_s is placed on the same phase where the reactive load is (Fig. 7), line current in phase 3 of the generator is eliminated, and the line currents are:

$$\overline{I}_1''' = 46 \cdot e^{j0^o}\,(A) \quad \overline{I}_2''' = 115 \cdot e^{-j120^o}\,(A) \quad \overline{I}_3''' = 0 \tag{36}$$

Positive-sequence component of such currents is the same expressed by (27) and (32). There are no reactive currents in that power system. And unbalance currents in that power system are:

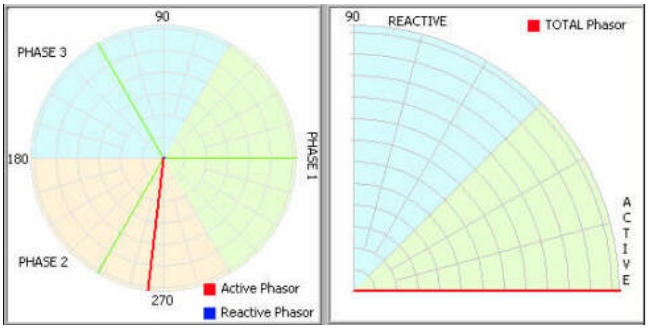
$$\overline{I}_{u1}''' = 7.59 \cdot e^{-j180^o}\,(A) \quad \overline{I}_{u2}''' = 61.18 \cdot e^{-j120^o}\,(A) \quad \overline{I}_{u3}''' = 53.59 \cdot e^{-j60^o}\,(A) \tag{37}$$

It is observed that unbalance currents have been decreased. Active power is not modified and reactive power has been fully compensated. Phasor total unbalance power:

$$\begin{aligned} \overline{A}_U''' &= \overline{A}_{Ucapacitor} + \overline{A}_{U\,load} = \\ &= -\sqrt{2} \cdot 230^2 \cdot \left(\left| \overline{Q}_c \cdot a \right| \right) \overline{q} + \overline{A}_{U\,load} = 32.6 \cdot e^{j0^o}\,(kVAa) \end{aligned}$$

(38)

is less than with the other compensators since unbalance caused by the reactive loads has been eliminated and unbalance power caused by active loads has not changed (Fig.8). Thus, this is the best reactive compensator, since it minimizes the line currents, power losses and non-useful powers and maximizes the efficiency improvement.



a) **b)**

Fig. 8. Phasor total unbalance power: a) active and reactive components importance in the phases, b) angle of phasor total.

5. CONCLUSIONS

Reactive and unbalance phenomena in sinusoidal three-phase, unbalanced at loads circuits with different reactive compensation topologies have been studied in this paper. Also, utility of phasor total unbalance power has been probed for analyzing unbalance phenomenon. This complex quantity is able to measure the unbalances due to the active loads by separating of those caused by the reactive loads, giving up information about the relative importance of those loads in the unbalance phenomena. Also this complex quantity indicates the phase or phases most unbalanced, so much due to the active loads as yield by the reactive loads.

By using the phasor total unbalance power in three-phase unbalanced at loads circuits with reactive power compensators, the following can be told:

- Power capacitors for circuit reactive compensation reduce and minimize reactive powers and currents independently of their placement.
- Compensator topology does not have influence on the reactive phenomenon, but unbalance phenomenon can be affected.
- Three-phase balanced power capacitors, generally used for reactive compensation in industrial utilities, do not affect to unbalance powers and currents.
- Single-phase power capacitors have influence on the unbalance phenomenon, increasing or decreasing their effects depending on your placement. When the capacitor is shunt-connected to the reactive load, unbalance power and currents are reduced and the efficiency is strongly improved, but when the capacitor is placed in a different phase where the reactive load is, unbalance phenomenon effects are increased and the efficiency can be reduced.
- There are no reactive current in three-phase circuits with total reactive compensation, even though some line currents are phase-shift 90 degrees with respect your phase voltage.

REFERENCES

[1] V. León-Martínez, J. Giner-García, J. Montañana-Romeu, A. Cazorla-Navarro. “Efficiency in electrical installations: New power definitions”. Mundo Electrónico Revue, nº 322, July 2001, pp. 28-32.

[2] A.E. Emanuel, “Apparent Powers Definitions for Three-Phase Systems”. IEEE Trans. on Power Delivery, Vol. 10, nº 3, July 1999, pp. 767-772.

[3] J.L. Willems, J.A. Ghijselen, A.E. Emanuel. “The Apparent Power Concept and the IEEE Standard 1459-2000”. IEEE Transactions on Power Delivery, Vol. 20, nº 2, April 2005, pp.876-884.

[4] S. Pajic, A.E. Emanuel. “Modern Apparent Power Definitions: Theoretical Versus Practical Approach – The General Case”. IEEE Trans on Power Delivery, Vol. 21, nº 4, October 2006, pp. 1787-1782.

[5] C.L. Fortescue. “”Method of symmetrical components as applied to the solution of polyphase networks”. AIEE 37, 1918, pp.1027.

[6] L.S. Czarnecki. “Physical Interpretation of the Reactive Power in Terms of the CPC Power Theory”. Electrical Power Quality and Utilisation Journal, Vol. XIII, nº 1, 2007, pp. 89-95.

[7] L.S. Czarnecki. “Powers of Asymmetrically Supplied Loads in Terms of the CPC Power Theory”. Electrical Power Quality and Utilisation Journal, Vol.XIII, nº 1, 2007, pp. 97-104.

[8] L.S. Czarnecki. “Orthogonal Decomposition of the Current in Three-Phase Non-Linear Asymmetrical Circuit with Nonsinusoidal Voltage”. IEE Trans. on Instr. and Meas. Vol. 37, nº 1, March 1988, pp. 30-34.

[9] V. León-Martínez, J. Montañana-Romeu, A. Cazorla-Navarro, J. Giner-García, J. Roger-Folch. “Phasor Total Unbalance Power: Formulation and some Properties”. IMTC 2007. Warsow, 1-3 May 2007.

[10] J. Montañana-Romeu, V. León-Martínez, J. Giner-García, A. Cazorla-Navarro. “Measurement of Energies Associated of Power Quality with Unbalanced and Nonsinusoidal Volatges in Electric Power Systems”. 14th PSCC, Sevilla, 24-28 June, 2002.

[11] V. León-Martínez. “Integral Method for the Efficiency and Power Quality Improvement on the Electric Energy Supply at Low Voltage”. Doctoral Thesis. Universidad Politécnica Valencia (Spain). September, 1997.

[12] IEEE Standard 1459-2000. “IEEE Trial-Use Standard for the Measurement of Electrical Power Quantities under Sinusoidal, Nonsinusoidal, Balanced and Unbalanced Conditions”.

[13] V. León-Martínez, J. Montañana-Romeu, A. Cazorla-Navarro. “Procedure and system of practical enable for the measurement of the unbalance power in electrical installations and its calibration device”. Oficina Española de Patentes y Marcas, PCT/ES2008/000296, ES 2 166 670B1. April 2007.

[14] J. Montañana-Romeu, V. León-Martínez. “Simpelec 5: Software for the measurement of powers, energies, efficiency and power quality in electrical installations”. Protected by Universidad Politécnica Valencia.