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Compensation of three- phase unsymmetrical currents systems with symmetric al voltage (direct)

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Abstract. The power analysis of the entire three-phase electrical system provides brief indications due to the compensation between the phases of the system of active and reactive powers. Only analysis of the electrical phases characteristics (currents, voltages, powers) of the three-phase system has theoretical and practical particular importance for balancing systems as well as analyzing the currents and powers that load the phases of the system. Akagi's "imaginary reactive power" method offers low efficiency and is polluting, introducing three order parasitic harmonics (compensating currents containing only half of the currents to be compensated) for three-phase unsymmetrical systems.

1. Compensation with reactive element

The classical method of simmering the unbalanced currents in the case of a pure resistive receiver connected to the line voltage (Figure 1(a)) is known for compensating the inverse current by means of a capacitor and a coil connected to form a connection in triangle with resistor.

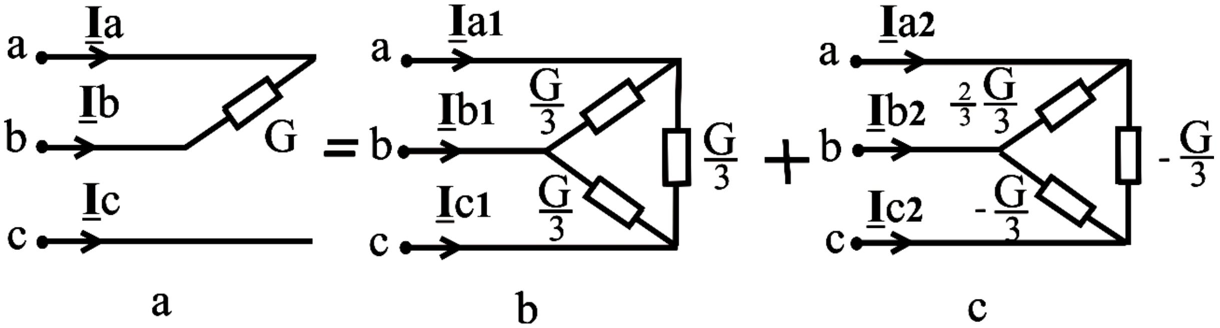

Figure 1 Example of decomposition of unbalanced scheme

The unbalanced scheme (Figure 1(a)) consists of an equivalent scheme (Figure 1(b)) consisting of three sides having equal conductances (G / 3) that the active power is identical to the one in the unbalanced scheme and an unbalanced receive scheme with zero total power and symmetrical inverted currents (Figure 1 (c)). The phase and line voltages of the three schemes are identical so that overlapping of currents, conductances and powers is simultaneous. Out of obvious relationships

$$\underline{I}_a = G\underline{U}_{ab} = \underline{I}_{a1} + \underline{I}_{a2} \tag{1}$$

with $\underline{I}_a = G\underline{V}_a$ because the equivalent star scheme has the side conductance $3(G/3) = G$ results

$$\underline{I}_{a2} = G\left(\underline{U}_{ab} - \underline{V}_a\right) = -G \cdot \underline{V}_b = -Ga^2\underline{V}_a \tag{2}$$

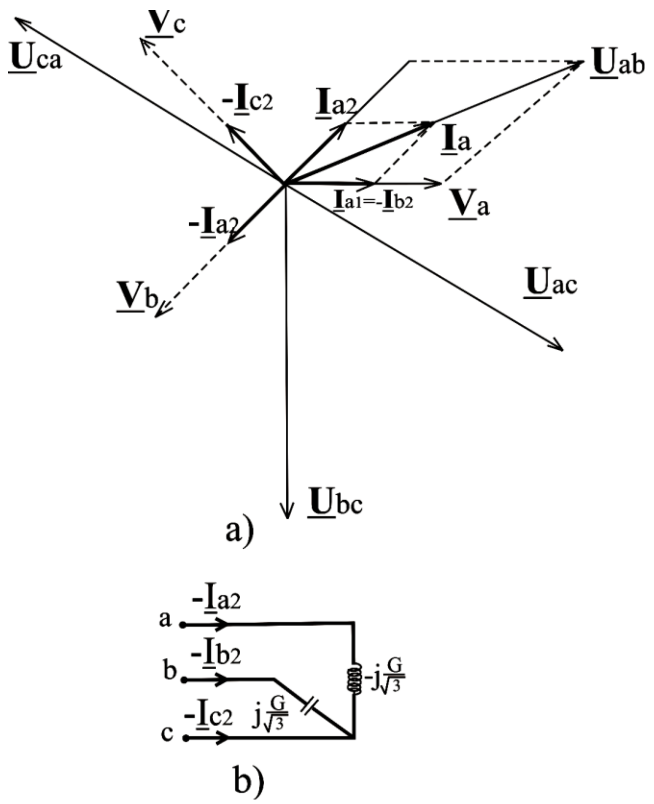

Figure 2 Compensation of the inverse current components

Figure 2(a) shows the currents:

$\underline{I}_a = \underline{I}_{a1} + \underline{I}_{a2}$

These relationships also result from the equivalent schemes in Figure 1(b) and 1(c).

$$\underline{I}_{a2} = -j\frac{G}{\sqrt{3}}\underline{U}_{ab} - \frac{G}{3}\underline{U}_{ac} = \frac{\underline{V}_a}{3}\left[2G\left(1-a^2\right) - G(1-a)\right] = -Ga^2\underline{V}_a \tag{3}$$

The reactive element diagram in Figure 2(b) performs the compensation of the inverse current components in Figure 1(c). In reality

$$\begin{aligned} -\underline{I}_{a2} &= -j\frac{G}{\sqrt{3}}\underline{U}_{ac} = -j\frac{G}{\sqrt{3}}V_a(1-a) = -j\frac{G}{\sqrt{3}}V_a \cdot j\sqrt{3}a^2 = Ga^2\underline{V}_a \\ -\underline{I}_{b2} &= j\frac{G}{\sqrt{3}}\underline{U}_{bc} = j\frac{G}{\sqrt{3}}V_a\left(a^2 - a\right) = j\frac{G}{\sqrt{3}}V_a \cdot \left(-j\sqrt{3}a^2\right) = Ga\underline{V}_a = -a\underline{I}_{a2} \end{aligned} \tag{4}$$

The general imbalance characterized by different conductances G_{ab}, G_{bc}, G_{ca} is solved by highlighting a balanced scheme associated with direct and other unbalanced currents associated with inverse currents (Figure 3 (a), (b), (c)).

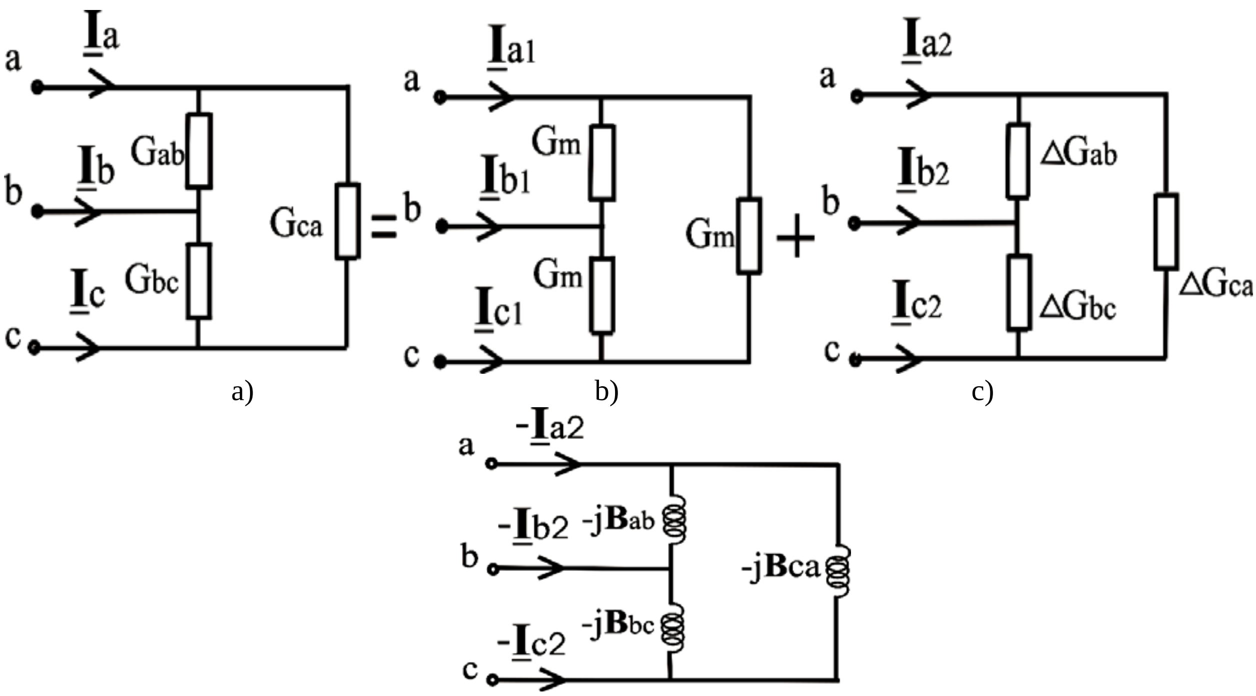

Fig. 3 Scheme associated with direct and other unbalanced currents associated with inverse currents

With

$$G_m = \frac{G_{ab} + G_{bc} + G_{ca}}{3} \tag{5}$$

result

$$\Delta G_{ab} = G_{ab} - G_m, \qquad \Delta G_{bc} = G_{bc} - G_m, \qquad \Delta G_{ca} = G_{ca} - G_m \tag{6}$$

The inverse current $\underline{I}_{a2}$ has the following expression

$$\begin{aligned} \underline{I}_{a2} &= \Delta G_{ab}\underline{U}_{ab} + \Delta G_{ca}\underline{U}_{ca} = \underline{V}_a\left[\Delta G_{ab}\left(1-a^2\right) + \Delta G_{ca}\left(1-a\right)\right] = \\ &= \underline{V}_a\left[\frac{3}{2}\left(\Delta G_{ab} + \Delta G_{ca}\right) + j\frac{\sqrt{3}}{2}\left(\Delta G_{ab} - \Delta G_{ca}\right)\right] = \\ &= \underline{V}_a\frac{\sqrt{3}}{2}\left[-\sqrt{3}\Delta G_{bc} + j\left(\Delta G_{ab} - \Delta G_{ca}\right)\right] \end{aligned} \tag{7}$$

For the equivalent reactive scheme with susceptance necessary to compensate inverse currents (Figure 3 (d)), it is necessary

$$-\underline{I}_{a2} = \underline{V}a\frac{\sqrt{3}}{2}\left[-j\sqrt{3}B_{bc} - \left(B_{ab} - B_{ca}\right)\right] \tag{8}$$

Result

$$B_{bc} = -\frac{\Delta G_{ab} - \Delta G_{ac}}{\sqrt{3}} \tag{9}$$

With circular movement have

$$B_{ca} = -\frac{\Delta G_{bc} - \Delta G_{ba}}{\sqrt{3}}, \qquad B_{ab} = -\frac{\Delta G_{ca} - \Delta G_{cb}}{\sqrt{3}} \tag{10}$$

Due to the relationship $\Delta G_{ab} + \Delta G_{bc} + \Delta G_{ca} = 0$ we will use in the following relations only two independent sizes

$$\Delta G = \Delta G_{ab} \text{ and } \alpha = -\frac{\Delta G_{bc}}{\Delta G_{ab}} \Delta G \tag{11}$$

Result $\Delta G_{ca} = -(1-\alpha)\Delta G$.

The equivalent schemes associated with the reversed current components are those shown in Figure 4.

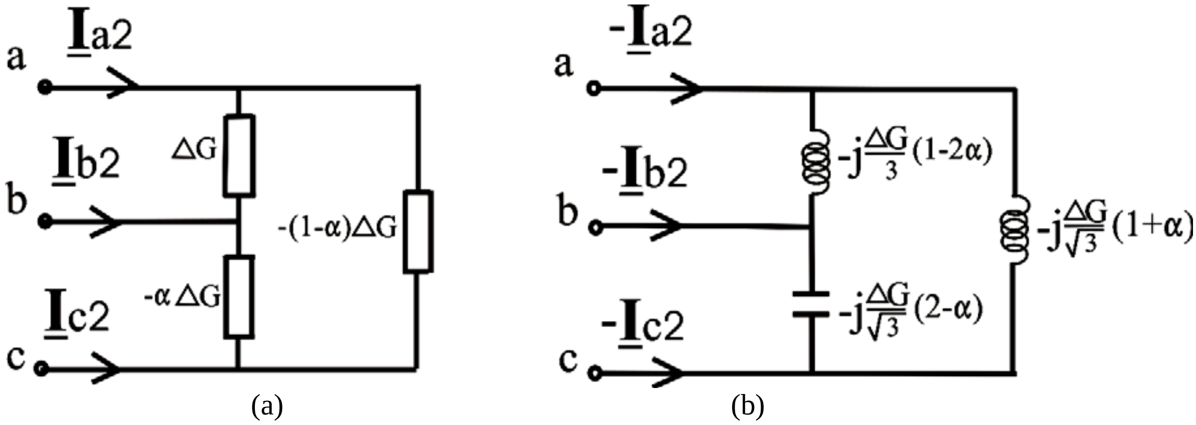

Fig. 4 The equivalent schemes associated with the reversed current components

$$-jB_{ab} = -j\frac{\Delta G}{\sqrt{3}}(1-2\alpha), \qquad -jB_{bc} = j\frac{\Delta G}{\sqrt{3}}(2-\alpha), \qquad -jB_{ca} = j\frac{\Delta G}{\sqrt{3}}(1+\alpha) \tag{12}$$

Figure 4 (b) contains the reactive elements necessary for balancing (compensation of the inverse components of the currents). Experimental determination of ΔG and α parameters results from measurements of powers.

With

$$\begin{aligned} \underline{I}_{a2} &= \sqrt{3}V_a\left[\frac{\sqrt{3}}{2}\alpha + j\left(1-\frac{\alpha}{2}\right)\right]\Delta G = \sqrt{3}\Delta G V_a\left[j - \alpha\left(\frac{j}{2}-\frac{\sqrt{3}}{2}\right)\right] = \\ &= \sqrt{3}\Delta G V_a\left[j + \alpha\left(-\frac{j}{2}+\frac{\sqrt{3}}{2}\right)\right] = \sqrt{3}\Delta G V_a\left[j + \alpha\angle -30^0\right] = \sqrt{3}\Delta G V_a\left[j + \alpha\angle 150^0\right] \end{aligned} \tag{13}$$

have

$$\begin{aligned} \Delta\underline{S}_a &= \underline{V}_a \underline{I}^*_{a2} = \sqrt{3}\Delta G V_a^2\left[\frac{\sqrt{3}}{2}\alpha - j\frac{2-\alpha}{2}\right] = \Delta P_a + j\Delta Q_a \\ \Delta\underline{S}_b &= \underline{V}_b \underline{I}^*_{b2} = a\Delta\underline{S}_a = \sqrt{3}\Delta G V_a^2\left[\frac{\sqrt{3}}{2}(1-\alpha) + j\frac{1+\alpha}{2}\right] = \Delta P_b + j\Delta Q_b \\ \Delta\underline{S}_c &= \underline{V}_c \underline{I}^*_{c2} = a^2\Delta\underline{S}_a = \sqrt{3}\Delta G V_a^2\left[-\frac{\sqrt{3}}{2} + j\frac{1-2\alpha}{2}\right] = \Delta P_c + j\Delta Q_c \end{aligned} \tag{14}$$

Or

$$\Delta P_a = \frac{3}{2}\Delta G V_a^2 \alpha \qquad \Delta Q_a = \sqrt{3}\Delta G V_a^2\left(-1+\frac{\alpha}{2}\right)$$

$$\Delta P_b = \frac{3}{2}\Delta G V_a^2 (1-\alpha) \qquad \Delta Q_b = \sqrt{3}\Delta G V_a^2\left(\frac{1+\alpha}{2}\right) \tag{15}$$

$$\Delta P_c = -\frac{3}{2}\Delta G V_a^2 \qquad \Delta Q_c = \sqrt{3}\Delta G V_a^2\left(\frac{1-2\alpha}{2}\right)$$

and

$$\Delta \underline{S}_a = \Delta \underline{S}_b = \Delta \underline{S}_c = \sqrt{3}\Delta G V_a^2 \sqrt{1+\alpha^2-\alpha}$$

From the expressions of power results the two parameters ΔG and α, characteristics of the imbalance

$$\Delta G = -\frac{2}{3}\frac{\Delta P_c}{V^2} \qquad \alpha = -\frac{\Delta P_a}{\Delta P_c} \tag{16}$$

Since the power measurements are made for the phases of the entire three-phase system of P_a, P_b, P_c and $P = P_a + P_b + P_c$, it is calculated

$$\Delta P_a = P_a - \frac{P_a + P_b + P_c}{3} \qquad \Delta P_b = P_b - \frac{P_a + P_b + P_c}{3}$$

$$\Delta P_c = P_c - \frac{P_a + P_b + P_c}{3} \tag{17}$$

With this, the two parameters ΔG and α are obtained.

If ΔG is the largest deviation from the medium value G

m, parameter α is the range of variation between 0 and 1 (0 <α <1). According to the expression of the complex representation of the inverse current, the geometric place (for α variable), its hodograph for the three phases is the sides of an isosceles triangle as represented in Figure 5.

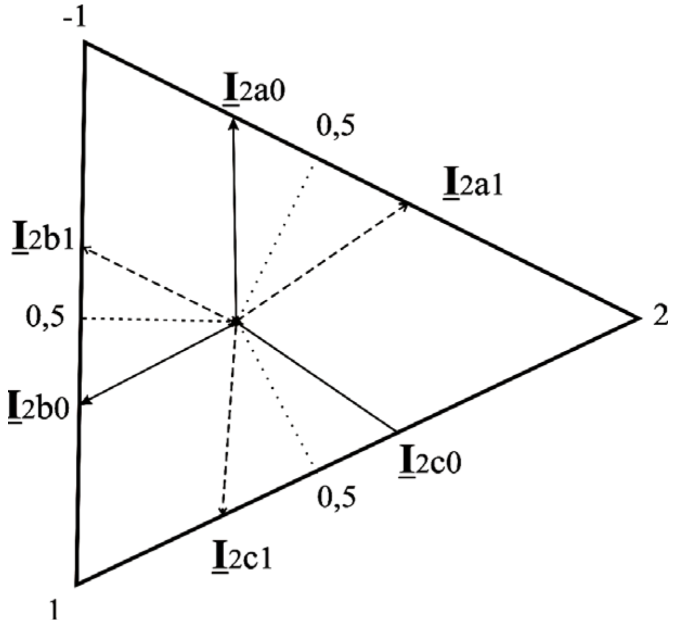

Figure 5

With the values of the measured powers and then of the parameters ΔG and α calculated, the values of the senses necessary for balancing the currents (reactive compensation of the inverse residual currents) are obtained (Figure 4(b)). Consequently, only the analysis of the parameters (currents, voltages, powers) characteristic of the three-phase system has theoretical and practical importance for balancing unbalanced systems as well as analyzing the currents and powers that load the phases of the system. The power analysis of the entire three-phase system provides brief, practically inefficient indications due to the compensation between the phases of the system of active and reactive phase powers.

2. Electronic Compensation of "Instantaneous Reactive Power

The concept of measurable reactive power for three-phase systems introduced by Iliovici since 1925 and accepted by C Budeanu only for the purpose of measuring reactive power, was resumed and expanded as meaning and use by H Akagi under the name "original instant power" or "instantaneous imaginary power". Although the method of compensating reactive components of symmetrical currents is efficient and useful in three-phase systems with symmetrical voltages for non-symmetric systems, it is questionable.

Initially, the author of the method used a biphasic component system. Subsequently, many authors used expressions with representative spatio-temporal vectors (Park vectors) to generalize the expression of powers of three-phase systems including imaginary reactive power without accentuating the limits of physical and technical validity of the obtained expressions. In a previous paper, the physical significance and prime technical utility of "instantaneous reactive power" was analyzed to compensate for symmetrical reactive currents. For non-symmetrical (inverse) currents, "instantaneous reactive" power compensation has low efficiency and is polluting (introduces third-order harmonics). For unbalance voltage, the pollutant effect is increased and compensation is not physically and technically possible.

In the following, unmanned voltages and current components are used to highlight the physical and technical limits of compensating symmetrical reactive currents and then compensating reverse inversion currents associated with unbalanced operation of the symmetrical voltage system.

2.1. Theory and technique of compensating symmetrical reactive currents

Compensation of symmetric reactive currents can be done economically instantly without the need for "imaginary reactive power".

For a symmetrical voltage system

$$u_\alpha = \sqrt{2}U \sin\omega t \qquad u_\beta = \sqrt{2}U \sin\left(\omega t - \frac{\pi}{2}\right) = -\sqrt{2}U \cos\omega t \tag{18}$$

and symmetrical currents decomposed into active and reactive components

$$\begin{aligned} i_\alpha &= \sqrt{2}I \sin(\omega t - \varphi) = \sqrt{2}I \cos\varphi \sin\omega t - \sqrt{2}I \sin\varphi \cos\omega t \equiv i_{\alpha p} + i_{\alpha q} \\ i_\beta &= -\sqrt{2}I \cos(\omega t - \varphi) = -\sqrt{2}I \cos\varphi \cos\omega t - \sqrt{2}I \sin\varphi \sin\omega t \equiv i_{\beta p} + i_{\beta q} \end{aligned} \tag{19}$$

it is the question of compensation of the reactive components of the currents

$$i_{\alpha q} = -\sqrt{2} I \sin\varphi \cos\omega t$$
$$i_{\beta q} = -\sqrt{2} I \sin\varphi \sin\omega t \qquad (20)$$

The total instantaneous power of the system associated with the reactive components of the symmetrical currents results in zero because the oscillating instantaneous powers of the symmetrical systems are self-compensated.

$$p = \frac{3}{2}\left(u_\alpha i_{\alpha q} + u_\beta i_{\beta q}\right) = \frac{3}{2}\left(-UI\sin\varphi \sin\omega t \cos\omega t + UI \sin\varphi \cos\omega t \sin\omega t\right) = 0 \qquad (21)$$

Therefore, if it is injected compensating current with the power electronics components

$$i'_{\alpha q} = -i_{\alpha q} \quad and \quad i'_{\beta q} = -i_{\beta q} \qquad (22)$$

device will not consume total instantaneous power . $p_c = -p = 0$

Akagi, starting from the expressions of active and total reactive powers (here in uncharted components, known as function of voltages (18) and current (19))

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{3}{2}\begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (23)$$

result by inversion the currents as functions of total powers

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3\Delta}\begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix}\begin{bmatrix} p \\ q \end{bmatrix} = \frac{2p}{3\Delta}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} + \frac{2q}{3\Delta}\begin{bmatrix} -u_\beta \\ u_\alpha \end{bmatrix} \equiv \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \qquad (24)$$

with

$$\Delta = u_\alpha^2 + u_\beta^2 - 2U^2 \qquad (25)$$

and

$$p = \frac{3}{2}\left(u_\alpha i_\alpha + u_\beta i_\beta\right) = 3UI\cos\varphi$$
$$q = \frac{3}{2}\left(-u_\beta i_\alpha + u_\alpha i_\beta\right) = -3UI\sin\varphi \qquad (26)$$

Obtein symmetrical reactive current components, identical to those previously expressed, are obtained in (20)

$$i_{\alpha q} = \frac{2}{3}\cdot\frac{q}{\Delta}\left(-u_\beta\right) = \frac{2}{3}\frac{\left(-3UI\sin\varphi\right)}{2U^2}\cdot\sqrt{2}U\cos\omega t = -\sqrt{2}I\sin\varphi\cos\omega t$$
$$i_{\beta q} = \frac{2}{3}\cdot\frac{q}{\Delta}u_\alpha = \frac{2}{3}\frac{\left(-3UI\sin\varphi\right)}{2U^2}\cdot\sqrt{2}U\sin\omega t = -\sqrt{2}I\sin\varphi\sin\omega t \qquad (27)$$

Consequently, the total reactive power q was used only to obtain reactive components of the offset currents. These can also be obtained by subtracting the active components from the total. The active components result from active instantaneous power, avoiding the use of reactive power (with erroneous results for non-symmetrical currents).

*2.2. **Compensation of non-symmetrical (reverse sequence)***

In case of a purely unbalanced receiver, supply from a three-phase symmetric voltage system, only the components of the reverse sequence currents must be compensated. The "imaginary reactive power" method offers low efficiency and is polluting by introducing "three parasitic" harmonics.

With direct symmetrical tensions

$$u_\alpha = \sqrt{2}U_1 \sin\omega t \qquad u_\beta = -\sqrt{2}U_1 \cos\omega t \tag{28}$$

and inverse symmetric currents

$$i_{\alpha 2} = \sqrt{2}I_2 \sin(\omega t + \delta_2) \qquad i_{\beta 2} = \sqrt{2}I_2 \cos(\omega t + \delta_2) \tag{29}$$

result

$$\begin{aligned} p &= \frac{3}{2}\left(u_\alpha i_\alpha + u_\beta i_\beta\right) = -3U_1 I_2 \cos(2\omega t + \delta_2) \\ q &= \frac{3}{2}\left(u_\alpha i_\beta - u_\beta i_\alpha\right) = 3U_1 I_2 \sin(2\omega t + \delta_2) \end{aligned} \tag{30}$$

compensatory currents $i_{\alpha q}$ *and* $i_{\alpha\beta}$ obtained by the Akagi method,

$$\begin{aligned} i_{\alpha q} &= \frac{-u_\beta}{\Delta} q = \sqrt{2}I_2 \cos\omega t \sin(2\omega t + \delta_2) = \frac{\sqrt{2}}{2} I_2 \left[\sin(\omega t + \delta_2) + \sin(3\omega t + \delta_2)\right] \\ i_{\beta q} &= \frac{u_\alpha}{\Delta} q = \sqrt{2}I_2 \sin\omega t \sin(2\omega t + \delta_2) = \frac{\sqrt{2}}{2} I_2 \left[\cos(\omega t + \delta_2) - \cos(3\omega t + \delta_2)\right] \end{aligned} \tag{31}$$

contain only half of the currents i_α *and* i_β which have to be compensated and appear in plus additional pollutants three harmonic.

2.3. Compensation of currents in non-symmetrical voltage systems

With

$$\begin{aligned} u_\alpha &= \sqrt{2}U_1 \sin\omega t + \sqrt{2}U_2 \sin(\omega t + \delta_2) \\ u_\beta &= -\sqrt{2}U_1 \cos\omega t + \sqrt{2}U_2 \cos(\omega t + \delta_2) \end{aligned} \tag{32}$$

result the determinant of matrix tension as pulsating function

$$\Delta = u_\alpha^2 + u_\beta^2 = 2\left[U_1^2 + U_2^2 - 2U_1 U_2 \cos(2\omega t + \delta_2)\right] \tag{33}$$

and in the particular case U_1=U_2, Δ is an oscillating function (it is canceled periodically) so that the compensation is not physically feasible.

3. Conclusions

Only analysis of the electrical phases characteristics (currents, voltages, powers) of the three-phase system has theoretical and practical particular importance for balancing systems as well as analyzing the currents and powers that load the phases of the system.

Power analysis of the entire three-phase system provides brief, practically inefficient indications due to the compensation between the phases of the system of active and reactive phase powers.

Akagi's "imaginary reactive power" method offers low efficiency and is polluting, introducing three order parasitic harmonics (compensating currents containing only half of the currents to be compensated) for three-phase unsymmetrical systems.

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