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Physical Interpretation of the Reactive Power in Terms of the CPC Power Theory

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Summary: Discussion on the physical interpretation of the reactive power *Q* is the subject of the paper. This power in common physical interpretation used to be associated with energy oscillation between the load and the supply source. The paper demonstrates that such interpretation is not correct. Just the opposite, the interpretation of the reactive power *Q* as an effect of energy oscillation is one of the major misinterpretations of power phenomena in electrical circuits. The Currents' Physical Components (CPC) power theory is the main theoretical tool used in the discussion presented in this paper.

1. INTRODUCTION

Although the physical interpretation of the reactive power Q in circuits with nonsinusoidal voltages and currents has been debated for a long time [1, 4, 11], physical interpretation of this power in single-phase circuits with sinusoidal voltages and currents seems to be as solid as the interpretation of the active power P. It is interpreted usually as the amplitude of energy oscillation between the load and the supply source.

This interpretation is a straightforward conclusion from the observation that with the voltage and current at the load terminals equal to:

$$u(t) = \sqrt{2}\, U \cos\omega_1 t \tag{1}$$

$$i(t) = \sqrt{2}\, I \cos(\omega_1 t - \varphi) \tag{2}$$

the instantaneous power of the load, meaning the rate of energy flow from the supply source to the load, can be expressed in the form:

$$p(t) = \frac{d}{dt} W(t) = u(t)\, i(t) = P(1 - \cos 2\omega_1 t) + Q \sin 2\omega_1 t \tag{3}$$

Therefore, it was not a surprise that when the author of this paper has turned attention in [5] to the known fact, that the instantaneous power $p(t)$ in three-phase circuits with balanced loads does not have any oscillating component, independently of the reactive power Q, Prof. Emanuel in a comment to [5] wrote in paper [8], "*...since nonactive power in the form of reactive power Q is also present and since Q affects the line power loss, the lack of oscillation of energy seems doubtful*, *hinting that the above conclusion needs to be carefully probed.*"

This is an important opinion on the energy oscillation as the cause of the reactive power, expressed also in various forms in other Emanuel's papers [2, 3], that might affect some views of the electrical engineering community on energy flow, because it was expressed by a worldwide known expert on powers and the chairman of the IEEE Committee that introduced IEEE Trial-Use Standard 1459 for power definitions.

Prof. Emanuel supported his confidence in the presence of energy oscillation as the cause of the reactive power Q in paper [8] using the Poynting Theorem. Unfortunately, he did not provide in that paper any credible proofs for the existence of energy oscillation in three-phase circuits with balanced loads. He demonstrates only that voltage-current products in three-phase systems, such as $u_R(t)i_R(t)$ have an oscillating component. However, as discussed in Ref. [9] and in Section 3, such products do not describe energy flow between the supply source and the load. Thus, in spite of common beliefs that the reactive power is caused by energy oscillation we have no proof for the existence of such an oscillation associated with the reactive power.

The lack of credible proof for the presence of oscillation of energy between balanced loads and the supply source has inspired the author of this paper to ask a heretic question: *In spite of such common physical interpretation, is the reactive power Q indeed caused by the energy oscillation?* Since the physical interpretation of the reactive power should be unique, independent on the circuit structure and properties, this question on the physical interpretation of reactive power Q applies not only to three-phase, but also to single-phase circuits, and not only to linear time-invariant (LTI) circuits, but also to nonlinear circuits and to circuits with time-variant parameters.

If indeed, the reactive power is not caused by energy oscillation and consequently, the association of this power with the energy oscillation is a major misinterpretation of power phenomena, it is easy to conclude how it happened.

Power properties of ac circuits and power definitions are used to be explained at the first courses of circuit analysis, based on properties of single-phase circuits with LTI loads. The relationship of the reactive power Q with the amplitude of energy oscillation is so officious in such circuits that, independently whether this is true or not, just this relationship provides a basis for the physical interpretation of reactive power. This interpretation is extrapolated next, without verification, to more complex circuits, where power properties are much more sophisticated and difficult for analysis. This process, repeated from generation to generation of electrical engineers' education for a century, causing even scientists to adhere to this interpretation with a kind of religious zeal.

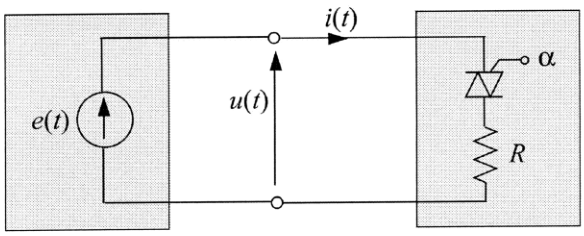

Fig. 1. Circuit with resistive load and TRIAC

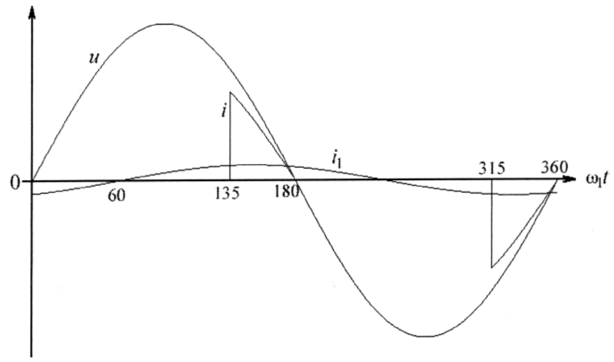

Fig. 2. Voltage and current in circuit shown in Figure 1

Therefore, let us verify whether there is a relationship between reactive power Q and energy oscillation in more complex circuits than only single-phase circuits with LTI loads or not.

2. CIRCUIT WITH TIME-VARIANT LOAD

Let us describe and explain energy flow related phenomena in the circuit shown in Figure 1. In this circuit, a purely resistive load is supplied from an ideal voltage source and its current is controlled by an ideal TRIAC, switched at firing angle a. Some properties of this circuit were discussed first in paper [5].

Assuming that the supply voltage is:

$$u(t) = 220\sqrt{2}\sin\omega_1 t \quad \text{V} \tag{4}$$

the load resistance $R = 1\Omega$ and firing angle $\alpha = 135$ deg, the current has the waveform shown in Figure 2.

The supply current RMS value is equal to:

$$||i|| = 66.28 \text{ A} \tag{5}$$

thus, the apparent power of the source, i.e., the product of the voltage and current RMS values, is:

$$S = ||u||\,||i|| = 220 \text{ x } 66.28 = 14.48 \text{ kVA} \tag{6}$$

Apart from higher order harmonics, the supply current contains a fundamental order harmonic:

$$i_1 = 26.0\sqrt{2}\sin(\omega_1 t - 60^0) \text{ A} \tag{7}$$

The supply current can be decomposed into physical components. Because the supply voltage is sinusoidal, this decomposition has only three physical components, without any scattered current, namely:

$$i = i_{1a} + i_{1r} + i_h \tag{8}$$

The component:

$$i_{1a} = 13.0\sqrt{2}\sin\omega_1 t \quad \text{A} \tag{9}$$

is the active current, i.e., a current in phase with the supply voltage. This component occurs in the supply current because the energy is permanently delivered from the source to the load.

The component:

$$i_{1r} = 22.5\sqrt{2}\cos\omega_1 t \quad \text{A} \tag{10}$$

is the reactive current, i.e., a current shifted by 90 deg with respect to the voltage. We cannot interpret it as an effect of energy oscillation, because the instantaneous power, meaning the rate of energy flow from the supply source to the load, equal to:

$$p(t) = \frac{dW(t)}{dt} = u(t)\,i(t) \tag{11}$$

is non-negative over the entire period T of the voltage and current variability. Thus there is no oscillation of energy in the circuit. Anyway, the load has no capability of energy storage. The reactive current occurs only because of the phase shift between the voltage and the current fundamental harmonic, but not because of energy oscillation.

The current last component:

$$i_h = i - i_1 = \sum_{n=2}^{\infty} i_n \tag{12}$$

is a load generated harmonic current. It occurs because the TRIAC in the load distorts the supply current from a sinusoidal waveform.

We have to be aware, however, that the current's physical components exist only as mathematical, but not as physical entities. Only the current i is a physical entity. It can be decomposed, in an infinite number of ways, into an infinite number of different mathematical entities. It would be an absurd however, to equip these mathematical entities with a physical existence and consider them as physical entities.

Nonetheless, the currents' physical components i_{1a}, i_{1r}, i_h, even if they are only mathematical entities, have properties that distinguish them from other components. They can be associated with distinctive physical phenomena and they are mutually orthogonal, hence their rms values fulfill the identity:

$$||i||^2 = ||i_{1a}||^2 + ||i_{1r}||^2 + ||i_h||^2 \tag{13}$$

Therefore, the rms value of the supply current and consequently, the apparent power S of the source, are effected only by the rms value of individual components. For the considered circuit:

$$\| i_{1a} \| = 13.0 \text{ A} \qquad \| i_{1r} \| = 22.5 \text{ A} \tag{14}$$

and:

$$\| i_h \| = \sqrt{\| i \|^2 - \| i_{1a} \|^2 + \| i_{1r} \|^2} = 61.0 \text{ A} \tag{15}$$

Multiplying eqn. (13) by the square of the supply voltage rms value, we obtain the power equation of the load in the form:

$$S^2 = P^2 + Q^2 + D_h^2 \tag{16}$$

with:

$$\begin{aligned} P &= \|u\| \, \|i_{1a}\| = 2.86 \text{ kW} \\ Q &= \|u\| \, \|i_{1r}\| = 4.95 \text{ kvar} \\ D_h &= \|u\| \, \|i_h\| = 13.42 \text{ kVA} \end{aligned} \tag{17}$$

Thus, there are two nonactive powers, meaning, the reactive power Q and load generated harmonic power D_h, in the circuit. These powers do not occur because of energy oscillation between the supply source and the load. Similarly as it is in the case of the apparent power S, there is no physical phenomenon characterized by these powers. These are only products of voltage rms value and the rms value of the reactive and the load generated harmonic currents. However, even not having any physical interpretation, these powers provide important information on how the reactive current and the load generated harmonic current contribute to an increase of the source apparent power in S. This increase is not due to energy oscillation, but due to the current fundamental harmonic phase-shift. It increases, at the same load active power P, the fundamental harmonic rms value. This rms value also increases due to generation of current harmonics by the TRIAC switch in the load. These harmonics contribute to the supply current rms value increase and consequently to an increase of the source apparent power, S.

There is one more reason for rejecting an opinion that reactive power is associated with energy oscillation, and consequently, that this oscillation degrades the power factor of the supply in the circuit considered. Namely, the reactive power of the load in Figure 1 can be compensated by a shunt capacitor, i.e., capacitor connected as shown in Figure 3.

Such a compensator, of the susceptance B for the voltage fundamental harmonic equal to:

$$\omega_1 C = \frac{Q}{U^2} = \frac{49.5 \times 10^3}{220^2} = 1.02 \text{ S} \tag{18}$$

compensates the reactive power, Q, and the reactive current i_{1r}, entirely. At the ideal voltage source, as assumed, the capacitor does not affect the load voltage and consequently, the active current i_{1a} and the harmonic current i_h remain unchanged. Thus, the capacitor changes the supply current to:

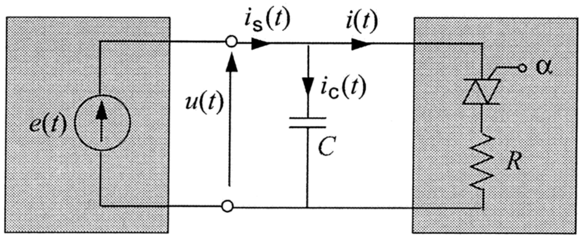

Fig. 3. Resistive load with capacitive compensator of reactive power

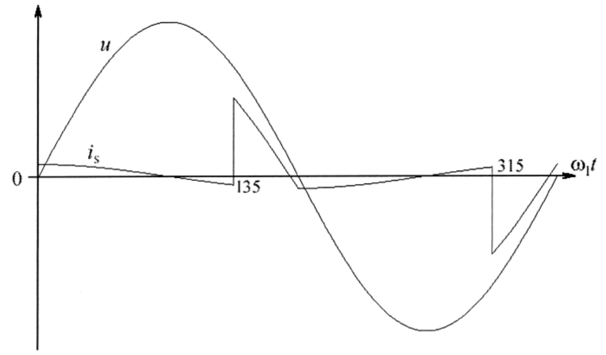

Fig. 4. The supply current waveform in a circuit with compensated reactive power, Q

$$i_s = i_{1a} + i_h \tag{19}$$

and reduces its rms from 66.28 A to:

$$\| i_s \| = \sqrt{\| i_{1a} \|^2 + \| i_h \|^2} = 62.37 \text{ A} \tag{20}$$

This reduces the apparent power from $S = 14.48$ kVA to $S = 13.72$ kVA and improves the power factor. The capacitor changes the supply current waveform as shown in Figure 4. Observe, that there are intervals of time when the voltage and the supply current are of the opposite sign, which means that the instantaneous power is negative, i.e., energy flows back to the supply source. It means that energy oscillation between the compensated load and the supply source has occurred. Thus, the reactive current i_{1r} was superseded in effect of compensation by the energy oscillation and this oscillation, instead of increasing the supply current rms value and degrading the power factor, λ, has improved it. Anyway, the energy oscillation in the compensated circuit is not accompanied by the reactive power Q.

3. THREE-PHASE CIRCUITS

The most common source of misinterpretation of power phenomena in three-phase, three-wire circuits, as shown in Figure 5, is the assumption that the voltage-current products such as $u_R(t)i_R(t)$, $u_S(t)i_S(t)$, and $u_T(t)i_T(t)$, are instantaneous powers, $p_R(t)$, $p_S(t)$ and $p_T(t)$, meaning the rates of energy flow to individual phases of a three-phase circuit.

A voltage-current product, say of the phase R, $u_R(t)i_R(t)$, is an instantaneous power $p_R(t)$, if only such a product, but

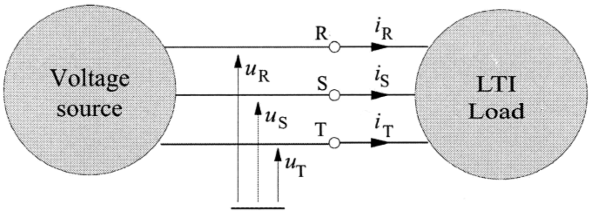

Fig. 5. Three-phase, three-wire circuit

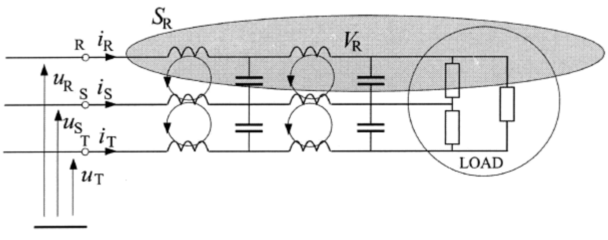

Fig. 6. Hypothetical space that confines phase R

nothing else, determines the rate dW_R/dt of energy flow to the space that confines this phase. It means the energy cannot enter that space by the other way but only by the port specified by terminal R and the ground. Because of mutual inductive and capacitive coupling of all phases as shown in Figure 6, and interconnections in the load, the energy flows to that space not only by the terminal port, but also by the entire surface that confines this space.

Consequently, the voltage-current product $u_R(t)i_R(t)$ does not specify the energy flow to the space V_R. Thus, this product:

$$u_R(t)\, i_R(t) \neq \frac{dW_R}{dt} = p_R(t) \tag{21}$$

cannot be considered as the instantaneous power. Such a product can be decomposed, of course, into the form:

$$u_R(t)\, i_R(t) = P_R\,(1-\cos 2\omega_1 t) + Q_R \sin 2\omega_1 t \tag{22}$$

It contains an "oscillating" component, but the terms:

$$P_R \triangleq U_R I_R \cos\varphi_R \qquad Q_R \triangleq U_R I_R \sin\varphi_R \tag{23}$$

similarly to the product $u_R(t)i_R(t)$, have no relation to the energy flow in the circuit. Observe moreover, that node voltages $u_R(t)$, $u_S(t)$, and $u_T(t)$, are relative quantities that can change with any change of the reference point, without affecting power phenomena. Thus it can be assumed, that:

$$u_R(t) \equiv 0 \qquad \text{so that:} \qquad u_R(t)\, i_R(t) \equiv 0 \tag{24}$$

Consequently, any consideration of a three-phase circuit as composed of three single-phase circuits could lead to a major misinterpretation of power phenomena in such a circuit. It has to be considered as a single three-phase entity. The instantaneous power $p(t)$ is the rate of energy flow to a whole three-phase load, i.e.:

$$p(t) \triangleq \frac{dW}{dt} = \boldsymbol{u}^{T}\boldsymbol{i} = u_R(t)\, i_R(t) + u_S(t)\, i_S(t) + u_T(t)\, i_T(t) \tag{25}$$

where $\boldsymbol{u}$ and $\boldsymbol{i}$ denote vectors of the voltage and current instantaneous values at the load terminals, R, S and T. The upper index T denotes a transposed matrix. The instantaneous power, defined only in such a way, is independent on the voltage reference point.

Let us investigate how the Currents' Physical Components power theory [7, 10] describes oscillation of energy between the supply source and three-phase, three-wire loads.

According to the CPC power theory, the vector of the line currents $\boldsymbol{i}$ of a three-phase LTI load supplied from a symmetrical source of a sinusoidal voltage $\boldsymbol{u}$:

$$\boldsymbol{u} \triangleq \begin{bmatrix} u_R \\ u_S \\ u_T \end{bmatrix} = \sqrt{2}\,\mathrm{Re}\begin{bmatrix} U_R \\ U_S \\ U_T \end{bmatrix} e^{j\omega_1 t} \triangleq \sqrt{2}\,\mathrm{Re}\,\boldsymbol{U}\, e^{j\omega_1 t} \tag{26}$$

of the three-phase rms value:

$$||\boldsymbol{u}|| \triangleq \sqrt{\frac{1}{T}\int_0^T \boldsymbol{u}^{T}(t)\cdot\boldsymbol{u}(t)\, dt} = \sqrt{U_R^2 + U_S^2 + U_T^2} \tag{27}$$

is composed of the active, reactive and the unbalanced currents:

$$\boldsymbol{i} \equiv \boldsymbol{i}_a + \boldsymbol{i}_r + \boldsymbol{i}_u \tag{28}$$

When the load has the active power P, then the active current is:

$$\boldsymbol{i}_a \triangleq \sqrt{2}\,\mathrm{Re}\{G_e\, \boldsymbol{U}\, e^{j\omega_1 t}\} \tag{29}$$

where:

$$G_e \triangleq \frac{P}{||\boldsymbol{u}||^2} = \mathrm{Re}\{Y_{ST} + Y_{TR} + Y_{RS}\} \tag{30}$$

while $\boldsymbol{Y}_{RS}$, $\boldsymbol{Y}_{ST}$ and $\boldsymbol{Y}_{TR}$ are line-to-line admittances of the load.

When the load has a reactive power Q, then the supply current contains a reactive component:

$$\boldsymbol{i}_r \triangleq \sqrt{2}\,\mathrm{Re}\{\, jB_e\, \boldsymbol{U}\, e^{j\omega_1 t}\,\} \tag{31}$$

where:

$$B_e \triangleq -\frac{Q}{||\boldsymbol{u}||^2} = \mathrm{Im}\{Y_{ST} + Y_{TR} + Y_{RS}\} \tag{32}$$

When the load is unbalanced and consequently, the supply current is asymmetrical, then this current contains an unbalanced component:

$$\boldsymbol{i}_u \triangleq \sqrt{2}\,\mathrm{Re}\{A\, \boldsymbol{U}^{\#} e^{j\omega_1 t}\,\} \tag{33}$$

where:

$$A \triangleq Ae^{j\psi} \triangleq -(\boldsymbol{Y}_{\rm ST} + \alpha\boldsymbol{Y}_{\rm TR} + \alpha^{*}\boldsymbol{Y}_{\rm RS}) \quad \alpha \triangleq 1\, e^{j120^0} \tag{34}$$

is an unbalanced admittance of the load, and:

$$\boldsymbol{U}^{\#} \triangleq \begin{bmatrix} \boldsymbol{U}_{\rm R} \\ \boldsymbol{U}_{\rm T} \\ \boldsymbol{U}_{\rm S} \end{bmatrix} \tag{35}$$

The active, reactive and the unbalanced currents are mutually orthogonal, meaning their scalar products, defined generally for $\boldsymbol{x}$ and $\boldsymbol{y}$ vectors as:

$$(\boldsymbol{x},\boldsymbol{y}) = \frac{1}{T}\int_0^T \boldsymbol{x}^{\rm T}\boldsymbol{y}\, dt = \frac{1}{T}\int_0^T (x_{\rm R}\, y_{\rm R} + x_{\rm S}\, y_{\rm S} + x_{\rm T}\, y_{\rm T})\, dt \tag{36}$$

are equal to zero. Consequently, the rms values of these currents satisfy the relation:

$$||\boldsymbol{i}||^2 = ||\boldsymbol{i}_{\rm a}||^2 + ||\boldsymbol{i}_{\rm r}||^2 + ||\boldsymbol{i}_{\rm u}||^2 \tag{37}$$

Multiplying this equation by the square of the supply voltage rms value, $||\boldsymbol{u}||$, the power equation of a three-phase load:

$$S^2 = P^2 + Q^2 + D^2 \tag{38}$$

is obtained.

There are two nonactive powers in this equation. The reactive power:

$$Q \triangleq \pm ||\boldsymbol{u}||\cdot||\boldsymbol{i}_{\rm r}|| = -B_{\rm e}\, ||\boldsymbol{u}||^2 \tag{39}$$

and an unbalanced power:

$$D \triangleq ||\boldsymbol{u}||\cdot||\boldsymbol{i}_{\rm u}|| = A\, ||\boldsymbol{u}||^2 \tag{40}$$

These two powers are associated with the presence of the reactive and unbalanced currents.

A possible association of the current physical components with energy oscillation between the three-phase load and the supply source was raised for the first time and discussed in paper [6].

The rate of energy flow from the supply source to a three-phase load, meaning the instanta-neous power of such a load, can be expressed as a sum of instantaneous powers associated with the active, reactive and unbalanced currents, namely:

$$\frac{dW(t)}{dt} = p(t) = \boldsymbol{u}^{\rm T}\boldsymbol{i} = \boldsymbol{u}^{\rm T}(\boldsymbol{i}_{\rm a} + \boldsymbol{i}_{\rm r} + \boldsymbol{i}_{\rm u}) \triangleq p_{\rm a}(t) + p_{\rm r}(t) + p_{\rm u}(t) \tag{41}$$

Assuming that:

$$\boldsymbol{u} = \begin{bmatrix} u_{\rm R} \\ u_{\rm S} \\ u_{\rm T} \end{bmatrix} = \sqrt{2}\, U \begin{bmatrix} \sin\omega_1 t \\ \sin(\omega_1 t - 120^0) \\ \sin(\omega_1 t + 120^0) \end{bmatrix} \tag{42}$$

and consequently:

$$\boldsymbol{i}_{\rm a} = \begin{bmatrix} i_{\rm Ra} \\ i_{\rm Sa} \\ i_{\rm Ta} \end{bmatrix} = \sqrt{2}\, G_{\rm e} U \begin{bmatrix} \sin\omega_1 t \\ \sin(\omega_1 t - 120^0) \\ \sin(\omega_1 t + 120^0) \end{bmatrix} \tag{43}$$

the instantaneous power associated with the active current:

$$p_{\rm a}(t) \triangleq \boldsymbol{u}^{\rm T}\boldsymbol{i}_{\rm a} = 3G_{\rm e}\, U^2 = P = \text{const.} \tag{44}$$

It means that permanent delivery of energy to the load, in the absence of the reactive and unbalanced currents, is not associated with any energy oscillation.

At the voltage as assumed, the reactive current is:

$$\boldsymbol{i}_{\rm r} = \begin{bmatrix} i_{\rm Rr} \\ i_{\rm Sr} \\ i_{\rm Tr} \end{bmatrix} = \sqrt{2}\, B_{\rm e} U \begin{bmatrix} \cos\omega_1 t \\ \cos(\omega_1 t - 120^0) \\ \cos(\omega_1 t + 120^0) \end{bmatrix} \tag{45}$$

Hence, the instantaneous power associated with the reactive current is equal to:

$$p_{\rm r}(t) \triangleq \boldsymbol{u}^{\rm T}\boldsymbol{i}_{\rm r} \equiv 0 \tag{46}$$

It means that no energy flow between the load and the supply source can be associated with the presence of the reactive current $\boldsymbol{i}_{\rm r}$ and the reactive power Q.

At the voltage as assumed, the unbalanced current is:

$$\boldsymbol{i}_{\rm u} = \begin{bmatrix} i_{\rm Ru} \\ i_{\rm Su} \\ i_{\rm Tu} \end{bmatrix} = \sqrt{2}\, AU \begin{bmatrix} \sin(\omega_1 t + \Psi) \\ \sin(\omega_1 t + \Psi + 120^0) \\ \sin(\omega_1 t + \Psi - 120^0) \end{bmatrix} \tag{47}$$

Hence, the instantaneous power associated with the unbalance current is equal to:

$$p_{\rm u}(t) \triangleq \boldsymbol{u}^{\rm T}\boldsymbol{i}_{\rm u} = -3AU^2\cos(2\omega_1 t + \psi) = -D\cos(2\omega_1 t + \psi) \tag{48}$$

Thus, energy oscillation between the load and the supply source is associated only with the presence of the unbalanced current. Consequently:

$$\frac{dW(t)}{dt} = p(t) = \boldsymbol{u}^{\rm T}\boldsymbol{i} = P - D\cos(2\omega_1 t + \psi) \tag{49}$$

It means that energy oscillation between three-phase loads and the supply source can occur in a sinusoidal situation only as an effect of the supply current asymmetry, but not as the effect of the presence of the reactive power Q.

Even if the reactive power cannot be associated with energy oscillation, one could blame the energy oscillation caused by the supply current asymmetry for a decline in the power factor. Therefore, let us check whether this decline could be explained in terms of this oscillation. Let us consider

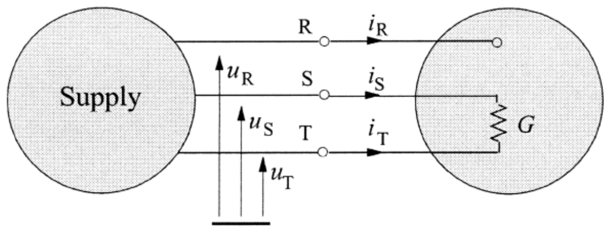

Fig. 7. Three-phase circuit with unbalanced resistive load

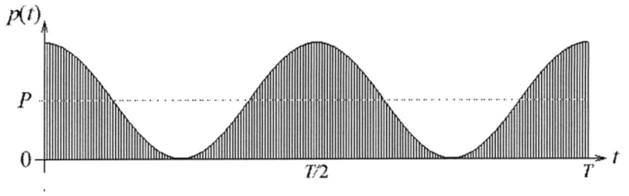

Fig. 8. Instantaneous power variability at supply terminals in circuits shown in Figure 7

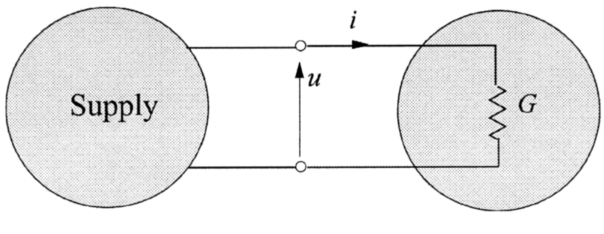

Fig. 9. Single-phase circuit with resistive load

for this purpose a simple three-phase circuit with an unbalanced resistive load as shown in Figure 7.

For such a circuit:

$$G_e = \mathrm{Re}\{\boldsymbol{Y}_{ST}\} = G, \qquad \boldsymbol{A} = -\boldsymbol{Y}_{ST} = G\, e^{j180^0}, \tag{50}$$

and consequently, the load active and unbalanced powers have the same value, respectively:

$$P = G_e\,||\boldsymbol{u}||^2 = GU^2 \qquad D = A||\boldsymbol{u}||^2 = GU^2 \tag{51}$$

The power factor of such a load is equal to:

$$\lambda = \frac{P}{S} = \frac{P}{\sqrt{P^2 + D^2}} = \frac{1}{\sqrt{2}} = 0.71 \tag{52}$$

The instantaneous power of the load, equal to:

$$p(t) = \frac{dW}{dt} = P - D\cos(2\omega_1 t + \psi) = P\,(1 + \cos 2\omega_1 t) \tag{53}$$

changes as shown in Figure 8.

Thus, one would blame the oscillating component of the energy flow for the power factor decline. Such a conclusion is wrong, however. When a single-phase circuit shown in Figure 9 is supplied with sinusoidal voltage:

$$u\,(t) = \sqrt{2}\,U\cos\omega_1 t \tag{54}$$

then the energy in such a circuit flows in exactly the same way as in the three-phase circuit considered previously, while the power factor is equal to unity. Thus, a presence of an oscillating component in the energy flow does not affect the power factor.

It means, that the power factor in the considered three-phase circuit has declined from unity not because of the energy oscillation, but because the unbalanced current in that circuit has a non zero value. One should observe, however, that such a conclusion cannot be obtained when an erroneous definition of the apparent power S is used for the power factor calculation, meaning, one of the definitions:

$$S \triangleq U_R I_R + U_S I_S + U_T I_T \tag{55}$$

$$S \triangleq \sqrt{P^2 + Q^2} \tag{56}$$

known as arithmetic and geometric apparent powers. As demonstrated in paper [5], these two definitions provide an erroneous value for the power factor.

4. CONCLUSIONS

The presence of the reactive power Q in electric circuits should not be associated with energy oscillation between a load and a supply source. Although such an association is very common in popular interpretations of power phenomena in electrical circuits, the relation between energy oscillation and the reactive power is apparent. Reactive power is only an effect of the phase-shift between the voltage and current. As a result, the current has a component that increases the current rms value, but does not contribute to permanent energy transmission. In single-phase circuits with sinusoidal voltage and LTI loads, oscillation of energy accompanies this component, but this oscillation is not a cause of the reactive power Q. In three-phase circuits with similar loads the reactive power is not even accompanied with such an oscillation.

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