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Comments to the paper: Instantaneous p-q Theory for Compensating Nonsinusoidal Systems

Streszczenie. Artykuł pokazuje, że inerpretacja fizyczna chwilowej mocy biernej q, przedstawiona w arykule "Instantaneous p-q Theory for Compensating Nonsinusoidal Systems", opublikowanym przez E.H. Watanabe, H. Akagi oraz M Aredes'a w Przeglądzie Elektro-technicznym, R. 84, Nr. 6/2008, jest błędna. Domniemana w tym artykule "wymiana energii" między fazami układu trójfazowego nie jest możliwa, podobnie jak nie jest możliwe wirowanie energii wokól linii zasilającej. Artykuł ten pokazuje także, że Instantaneous p-q Theory nie tworzy popranych podstaw kompensacji przy niesinusoidalnym napięciu zasilania odbiorników trójfazowych.

Abstract. *The paper shows that the physical interpretation of the instantaneous reactive power q presented by E.H. Watanabe, H. Akagi and M Aredes in the paper "Instantaneous p-q Theory for Compensating Nonsinusoidal Systems", published in Przegląd Elektrotechniczny, R. 84, Nr. 6/2008, is erroneous. Alleged "exchanged" energy between phases of supply lines of a three-phase system is not possible. Also it is not possible for energy to rotate around such a line. The paper shows as well that the Instantaneous p-q Theory, in the presence of the supply voltage harmonics or asymmetry, does not provide fundamentals for switching compensator control.*

Słowa kluczowe: teoria chwilowej mocy biernej, teoria składowych fizycznych pradu, aktywne filtry mocy, compensatory kluczujące.
Keywords: instantaneous reactive power theory, CPC power theory, active power filters, switching compensators reactive power.

Introduction

Power properties of electrical systems are described in terms of powers. Relations between powers and power phenomena that shape these properties have become, however, extremely confusing. Various sets of powers were introduced to electrical engineering in the 20th century to explain and describe power properties of electrical systems.

The instantaneous active and reactive powers, p and q, are just two such powers used in the Instantaneous Reactive Power (IRP) p-q Theory [1,3 - 5] for describing power properties of three-phase loads supplied with three-wire line as shown in Fig. 1.
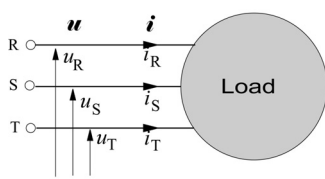

Figure 1. Three-phase load supplied with a three-wire line

According to this theory, these two powers provide information on power properties of the load, sufficient for controlling switching compensators, installed at load terminals for improving power properties of the distribution systems. The Authors of the IRP p-q Theory even claimed [3], that its development was a response to "*...the demand to instantaneously compensate the reactive power",* which means that the instantaneous active and reactive powers, p and q, identify power properties of three-phase loads instantaneously. A proof that this is not possible was presented in paper [6].

The instantaneous active power p is nothing else than the *instantaneous power*

$$(1) \qquad p(t) \triangleq \frac{dW(t)}{dt} = u_R(t) i_R(t) + u_S(t) i_S(t) + u_T(t) i_T(t) \;,$$

i.e., the rate of energy flow from the supply source to the load. It was introduced to electrical engineering much earlier than the IRP p-q theory was invented, so that change of the name of this quantity to *instantaneous active power* does not seem to be justified. Not only two different names for the same quantity may create a confusion, but first of all, it is not related to the active power P of the load. It exists independently whether the load indeed has the active power P or not.

Another power quantity introduced to electrical engineering by the IRP p-q Theory is the instantaneous reactive power q. It was introduced formally, as a mathematical entity, and it was originally referred to as *instantaneous imaginary power*. These two different terms, meaning *reactive* and *imaginary*, are regarded by Authors of paper [8] (Page 15, at the bottom of the left column), however, as synonyms.

The physical meaning of the instantaneous reactive power q, in early papers on IRP p-q theory was not provided. The only explanation of the physical meaning of the q-power, presented by Akagi and Nabae in Ref. [3] has the form:

> "*The instantaneous imaginary power q was introduced on the same basis as the conventional instantaneous real power p in three-phase circuits, and then the instantaneous reactive power was defined with the focus on the physical meaning and the reason for naming.*"

This sentence does not explain, of course, the physical meaning of the instantaneous reactive power q. The instantaneous (real) power p is the rate of energy flow, while any relation to energy flow has been provided in the interpretation of the instantaneous reactive power q.

To have a cognitive value, a power theory has to provide a physical interpretation of quantities used by that theory for describing power properties. Therefore, a quest for interpretation of the instantaneous reactive power q has a long history [2]. Unfortunately, any physical phenomenon in the load, associated with this power, was not yet identified. Only some circuit features and phenomena that cannot be responsible for this power were eliminated. In particular, the reactance elements in the load are not responsible for the presence of instantaneous reactive power q , because it can occur even if, as demonstrated in Ref. [6], the load is purely resistive.

Physical interpretation of *q*-power in Ref. [8]

The paper under discussion [8] provides (Page 15, the bottom paragraph in the left column), the following explanation of the instantaneous imaginary power q:

> "*…the imaginary power q is proportional to quantity of energy that is being exchanged between the phases of the system. Fig. 1 summarizes the above explanations about the real and imaginary powers.*"

Discussion on this explanation requires that the Fig. 1 is provided for Readers. That Figure, copied from paper [8], is shown below.
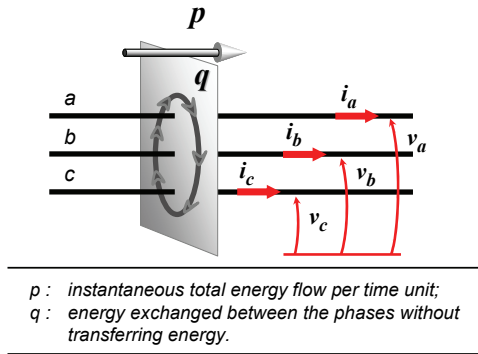

p : instantaneous total energy flow per time unit;
q : energy exchanged between the phases without
*   transferring energy.*

Fig. 1. Physical meaning of the instantaneous real and imaginary powers.

Discussion on interpretation given in Ref. [8]

The Reader may observe, however, that presented explanation of the meaning of the imaginary power q does not fit Figure 1, because in the text is told: "*energy is being exchanged between phases*" while Figure 1 is drawn in such a way as if this energy rotates around the supply line. Because this is not clear, we should verify, if any of these flows of energy is possible.

Flow of energy in electromagnetic fields was described [7] by J.H. Poynting in 1884. He introduced the concept of the Poynting Vector, specified as a vector product of the electric and magnetic field intensities, $\vec{E}$ and $\vec{H}$, namely

$$(2) \qquad \vec{P} = \vec{E} \times \vec{H} .$$

This vector specifies direction of surface density of the rate of energy flow in electromagnetic fields. The rate of energy flow through surface of area A is equal to

$$(3) \qquad \iint_A \vec{P} \bullet d\vec{A} \ = \ \frac{dW(t)}{dt} .$$

Thus, the energy in electromagnetic fields flows in the direc-tion of the Poynting Vector, which is at any point of a space perpendicular to the plane span on the vectors of electric and magnetic fields intensities at that point. It is perpen-dicular to each of them, as shown in Fig. 2.
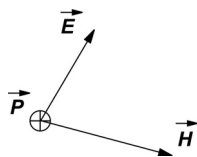

Figure 2. Orientation of electric and magnetic field intensities and the Poynting Vector

Now, let us check whether the situation shown in Fig.-1 of paper [8] is possible or not, meaning can the energy rotate around the supply line? Let us assume that the supply line, composed of conductors a, b and c, is a flat line.

If energy rotates around such a line, then the Pointing Vector at point x, in conductors a, b and c plane, should be perpendicular to that plane, as shown in Fig. 3. It is not possible, however, because the magnetic field intensity created by the line currents at point x is perpendicular to that plane, while these two vectors have to be perpendicular to each other. Thus, energy cannot rotate around the supply line.
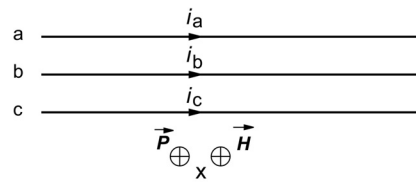

Fig. 3. Orientation of magnetic field intensity at point x in conductors plane

Let us verify now whether "*energy is being exchanged between phases…*" or not. If energy flows between phases, then the Poynting Vector should be perpendicular to conductors, meaning it should be oriented as shown in Fig. 4. Its sign for this discussion does not matter.
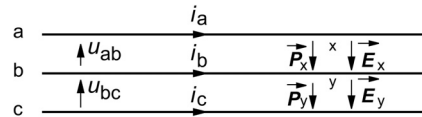

Fig. 4. Orientation of electric field intensity between conductors

When conductors are ideal, meanning their resistance is neglected, then the electric field intensity has to be perpendicular to the conductor surface. Thus, the Pointing Vector cannot be perpendicular to conductors, because it has to be perpendicular to the electric field intensity. Only when there is a resistance in the line conductors, then the electric field intensity has a component along conductor surface and the Poynting Vector has a component towards conductors. In such a case, some amount of energy flows to conductors, where it is dissipated as heat. It has nothing in common, however, with "*energy exchange between phases*"

Thus, this reasoning, based on a very fundamental principle of electromagnetic fields, demonstrates that the physical interpretation of the instantaneous imaginary power q, suggested in paper [8], is erroneous.

Compensation of oscillating component of instantaneous active power $\tilde{p}$

The IRP p-q Theory regards the oscillating component of the instantaneous active power $\tilde{p}$ as an undesirable component of the instantaneous active power p. Its elimination is one of compensation goals in the IRP p-q Theory. Effects of compensation of this component are demonstrated by Authors of paper [8] in Fig. 12 and 13. Unfortunately, there is the lack of justification in the paper [8] for the claim that the oscillating component of the instantaneous active power $\tilde{p}$ is an undesirable component.

Analysis of power properties of three-phase systems using tools developed in the Currents' Physical Components (CPC) power theory [9], does not confirm that claim. Let us prove it.

Since the Authors assure that IRP p-q Theory is developed assuming that "….*no restrictions are imposed on the voltage and current waveforms,..*" (Page 13, right column, the first paragraph), let us assume that a three-phase symmetrical voltage composed of the fundamental and the 5th order harmonic,

$$(4) \qquad \boldsymbol{u} = \boldsymbol{u}_1 + \boldsymbol{u}_5 = \begin{bmatrix} u_{1R} \\ u_{1S} \\ u_{1T} \end{bmatrix} + \begin{bmatrix} u_{5R} \\ u_{5S} \\ u_{5T} \end{bmatrix} ,$$

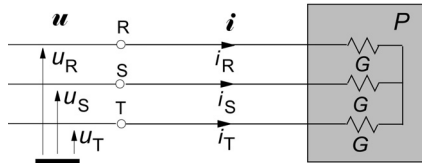is applied to a resistive balanced load shown in Fig. 5.

Figure 5. Balanced resistive load

Because the load is balanced, the vector of the supply current is equal to

$$(5) \qquad \boldsymbol{i} = G\boldsymbol{u} = G(\boldsymbol{u}_1 + \boldsymbol{u}_5)$$

The instantaneous (active) power of the load is

$$(6) \qquad p \triangleq \frac{dW}{dt} = \boldsymbol{u}^T \boldsymbol{i} = \boldsymbol{u}^T G \boldsymbol{u} = G[\boldsymbol{u}_1 + \boldsymbol{u}_5]^T[\boldsymbol{u}_1 + \boldsymbol{u}_5] =$$
$$= G(\boldsymbol{u}_1^T \boldsymbol{u}_1 + \boldsymbol{u}_5^T \boldsymbol{u}_5 + \boldsymbol{u}_1^T \boldsymbol{u}_5 + \boldsymbol{u}_5^T \boldsymbol{u}_1).$$

The first two terms are constant components of the instantaneous power

$$(7) \qquad G\boldsymbol{u}_1^T \boldsymbol{u}_1 = G\|\boldsymbol{u}_1\|^2 \triangleq P_1,$$

$$(8) \qquad G\boldsymbol{u}_5^T \boldsymbol{u}_5 = G\|\boldsymbol{u}_5\|^2 \triangleq P_5,$$

where P_1 and P_5 are harmonic active powers of the fundamental and the 5th order harmonics. The last term can be rearranged as follows

$$G(\boldsymbol{u}_1^T \boldsymbol{u}_5 + \boldsymbol{u}_5^T \boldsymbol{u}_1) = G(u_{1R}u_{5R} + u_{1S}u_{5S} + u_{1T}u_{5T}) +$$
$$+ G(u_{5R}u_{1R} + u_{5S}u_{1S} + u_{5T}u_{1T}) =$$
$$= 2G(u_{1R}u_{5R} + u_{1S}u_{5S} + u_{1T}u_{5T}) =$$
$$(9) \qquad = 4GU_1U_5[\cos\omega_1 t \times \cos 5\omega_1 t +$$
$$+ \cos(\omega_1 t - 120^0) \times \cos(5\omega_1 t + 120^0) +$$
$$+ \cos(\omega_1 t + 120^0) \times \cos(5\omega_1 t - 120^0)] =$$
$$= 6GU_1U_5 \cos 6\omega_1 t.$$

Eventually, the instantaneous power of the load is equal to

$$(10) \qquad p(t) = \frac{dW}{dt} = P_1 + P_5 + 6GU_1U_5\cos 6\omega_1 t = \bar{p} + \tilde{p},$$

thus, it has a non-zero oscillating component $\tilde{p}$. The same result can be obtained using IRP p-q Theory, but complicating the issue with the Clarke Transform is simply not needed for calculating the instantaneous power p.

The load shown in Fig. 5 is the best possible load, with unity power factor, $\lambda = P/S = 1$, meaning its active power P is equal to the apparent power S. According to IRP p-q Theory, its instantaneous active power p contains, however, an undesirable oscillating component $\tilde{p}$, which should be compensated.

It was demonstrated in paper [10], that a switching compensator, connected at terminals of the considered balanced resistive load, and controlled according to IRP p-q algorithm in such a way that it compensates the oscillating component $\tilde{p}$ of the active power p, injects a compensating current into the supply. This current reduces, of course, the power factor λ, originally equal to unity. The compensating current is, moreover, distorted.

It means, that in some situations such as that discussed above, the oscillating component $\tilde{p}$ of the instantaneous power p does not reduce the load power factor and should not be compensated.

Similar conclusions can be drawn for a situation, where the supply voltage applied to the load shown in Fig. 5 is

sinusoidal, but asymmetrical. It was demonstrated in paper [11], that the instantaneous power p of such a load also contains an oscillating component $\tilde{p}$, although the load power factor is unity.

Thus, the conclusion that the oscillating component of the instantaneous power p is undesirable and should be compensated, presented in paper [8], is not generally valid. This observation challenges the claim in **Conclusions**, that IRP p-q provides algorithm which enables compensation

"…*for three-phase loads to provide constant instantaneous active power to the source, even if the supply voltages are unbalanced and/or contain harmonics,*"

because it may not be a right goal of compensation.

Conclusions

The Instantaneous Reactive Power p-q Theory, as presented in paper [8], still does not provide any physical interpretation for the basic quantity it introduced to electrical engineering, meaning the instantaneous reactive power q. Also the conclusion, that the algorithm for switching compensator control is valid at nonsinusoidal and/or asymmetrical supply voltage is not correct. In the presence of the supply voltage harmonics or its asymmetry, any attempt of compensating the oscillating component of the active power causes generation of the control signal, which may reduce the power factor and distort the supply current.

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