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Leszek S. CZARNECKI
Life Fellow IEEE, Alfredo M. Lopez Distinguished Professor, Louisiana State University, USA, e-mail: lsczar@cox.net

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Powers and Compensation in Systems with Nonsinusoidal Voltages and Currents

Part 10. Development History of the Currents' Physical Components (CPC) - Based Power Theory

Moce i kompensacja w obwodach z odkształconymi i niesymetrycznymi przebiegami prądu i napięcia
Część 10. Historia rozwoju teorii składowych fizycznych prądów (CPC)

Streszczenie: *Teoria składowych fizycznych prądów (ang.: currents' physical components – CPC) i oparta na niej teoria mocy obwodów z niesinusoidalnymi i niesymetrycznymi przebiegami prądów i napięć stanowią teorię mocy, która wyjaśnia zjawiska fizyczne redukujące skuteczność przesyłu energii w systemach rozdzielczych. Powstawała ona równolegle do innych prób opisu właściwości energetycznych obwodów elektrycznych i jest obecnie najbardziej zaawansowaną koncepcją teorii mocy. Niniejszy artykuł osadza teorię składowych fizycznych prądów w szerszym kontekście rozwoju teorii mocy. Podsumowuje on także wkład różnych szkół w rozwój teorii mocy obwodów elektrycznych.*

Abstract: *Currents' Physical Components (CPC) – based power theory of electrical systems with nonsinusoidal and asymmetrical voltages and currents is a theory which explains power related physical phenomena that contribute to the reduction of effectiveness of the energy transfer in distribution systems. It was developed in parallel to other attempts aimed at explanation and description of power properties of electrical circuits and it is currently the most advanced concept of the power theory. This paper puts the development of the CPC in a broader context of the power theory development. It also summarizes contribution of various schools of power theory to its development.*

Słowa kluczowe: *teoria mocy, compensacja, niesinusoidalne prądy*

Keywords: *power theory, compensation, nonsinusoidal voltages*

1. INTRODUCTION

The concept of the Currents' Physical Components (CPC) has occurred as an answer to the question: **why could the apparent power S of a load be higher than its active power P?** This question, of cognitive nature, is one of the most fundamental questions of electrical engineering. The CPC-based power theory is the first power theory that provides the answer to this question; the answer which is based on physical fundamentals. Fryze suggested [9] that this question should be formulated with respect to the load current rather than with respect to the load powers, namely, **why can the rms value of the load current be higher than its value needed for the load supply with the active power P?** Fryze's rephrasing of the original question along with separation of the active current $i_a(t)$ was the first step towards development of the Currents' Physical Components – based power theory. The active current is one of seven Physical Components of the load current.

The power theory based on the concept of Currents' Physical Components is currently the most advanced tool that enables to explain physical phenomena which accompany energy transfer in distribution systems and describe them in power terms. It enables the identification of the causes of reduction in the effectiveness of this transfer in the presence of waveform distortion and asymmetry. It is also a tool used to design reactive compensators and to control switching compensators to improve this transfer effectiveness.

A lot of studies have contributed to the development of the CPC-based power theory, with results published over a few decades. One of the most important was the research conducted by Stanisław Fryze, a professor at Lwów University of Technology. The conclusions were published in Polish, 1931 and in German, 1932. It is worth mentioning that it was Fryze who introduced the term **"power theory"** into electrical engineering. His contribution to the power theory development was discussed in articles [41, 57].

This paper places, without going into details, the CPC-based power theory in a wider perspective of the power theory development. More details could be found in former papers of this series on Powers and Compensation in Circuits with Nonsinusoidal and Asymmetrical Voltages and Currents published in this Journal [56, 58, 59, 60, 63, 64, 66, 67].

2. CURRENTS' PHYSICAL COMPONETS

The identification of particular components of a load current which are associated with distinctive physical phenomena in the circuit or with its distinctive features is the very essence of the concept of the Currents' Physical Components (CPC). The plural term **"Currents"** was used in this name because CPC applies also to three-phase systems supplied by three-line currents. In the case of single-phase circuits the term **"Current Physical Components"** is more appropriate.

The load current in single-phase circuits has four Physical Components

$$i(t) = i_{\mathrm{Ca}}(t) + i_{\mathrm{Cr}}(t) + i_{\mathrm{Cs}}(t) + i_{\mathrm{G}}(t). \tag{1}$$

Index *"C"* means that Physical Components $i_{Ca}(t)$, $i_{Cr}(t)$, $i_{Cs}(t)$ can have only such harmonics for which the harmonic active power

$$P_n = U_n I_n \cos\varphi_n > 0 \ , \tag{2}$$

is positive, i.e., harmonics that transfer the energy exclusively from the supply source to the load. Harmonics that transfer the energy in the opposite direction, i.e., from the load to the supply source belong to the Current Physical Component with index *"G"*.

Each of the current components in decomposition (1) is associated with a distinctive physical phenomenon in the load and can be identified by measurement of the voltage and current at the load terminal. No knowledge of the load structure and parameters is needed for that. These are:

Active current $i_{Ca}(t)$, in linear, time-invariant (LTI) single-phase circuits this current is identical with the active current $i_a(t)$ which was identified by Fryze [9]. In non-linear or/and time variant loads the active current $i_{Ca}(t)$ differs from the Fryze's active current $i_a(t)$. The active current $i_{Ca}(t)$ is the Current Physical Component associated with the phenomenon of permanent transfer of energy from the supply source to the load. From the point of view of the energy transfer, it is the most important, indispensable component of the load current. Remaining Physical Components of the load current do not transfer energy permanently. They contribute only to useless loading of the supply source, thus these Physical Components are harmful.

Reactive current $i_{Cr}(t)$, in LTI circuits this current is identical with the reactive current $i_r(t)$ which was identified in the load current of single-phase circuits by Shepherd and Zakikhani [18]. It is the Current Physical Component associated with the phenomenon of the phase-shift between harmonics of the load voltage and current.

Scattered current $i_{Cs}(t)$ in LTI circuits this current is identical with the scattered current $i_s(t)$, which was identified in the load current of single-phase circuits by Czarnecki [23, 56]. It is the Current Physical Component associated with the phenomenon of the change of the load conductance G_n with harmonic order n.

Generated current $i_G(t)$, identified in the load current of non-linear and/or time-variant single-phase circuits by Czarnecki [31, 58]. It is the Current Physical Component associated with the phenomenon of the energy flow at harmonic frequencies from the load back to the supply source. This flow is caused by harmonics that occur in the load current due to the load non-linearity or periodic change of its parameters.

Decomposition (1) into CPC can be generalized for currents of three-phase loads, supplied both by a three-wire lines [28, 59] and by four-wire lines, i.e., with a neutral conductor [63 68].

Namely, when the line currents of a three-phase load are arranged into a three-phase vector

$$\boldsymbol{i}(t) = \begin{bmatrix} i_R(t) \\ i_S(t) \\ i_T(t) \end{bmatrix}, \quad (3)$$

then such a vector of the line currents of a load supplied by a four-wire line can be decomposed into seven Currents' Physical Components, namely:

$$\boldsymbol{i}(t) = \boldsymbol{i}_{Ca}(t) + \boldsymbol{i}_{Cr}(t) + \boldsymbol{i}_{Cs}(t) + \boldsymbol{i}_{G}(t) + \boldsymbol{i}^{n}_{Cu}(t) + \boldsymbol{i}^{p}_{Cu}(t) + \boldsymbol{i}^{z}_{Cu}(t). \quad (4)$$

The active, reactive, scattered and the generated currents $\boldsymbol{i}_{Ca}(t), \boldsymbol{i}_{Cr}(t), \boldsymbol{i}_{Cs}(t)$ and $\boldsymbol{i}_{G}(t)$ preserve their physical interpretation, only generalized to three-phase systems, though. Three new Currents' Physical Components occur [28, 59, 63, 68, 70].

Unbalanced symmetrical current of the negative sequence $\boldsymbol{i}^{n}_{Cu}(t)$. This Currents' Physical Component is associated with phenomenon of current asymmetry caused by the load imbalance which results in a symmetrical current component of the negative sequence.

Unbalanced symmetrical current of the positive sequence $\boldsymbol{i}^{p}_{Cu}(t)$. This Currents' Physical Component is associated with phenomenon of current asymmetry caused by the load imbalance in the presence of the supply voltage asymmetry, which results in a symmetrical current component of the positive sequence.

Unbalanced symmetrical current of the zero sequence $\boldsymbol{i}^{z}_{Cu}(t)$. This Currents' Physical Component is associated with phenomenon of current asymmetry caused by the load imbalance in the presence of the supply voltage asymmetry in systems with four-wire supply, which results in a symmetrical current component of the zero sequence.

The last CPC are not components of the same unbalanced currents but occur in different circuit situations. The first one can occur in three-wire systems even if the supply voltage is symmetrical, the second can occur in the same systems when the supply voltage is asymmetrical. The last one can occur only in four-wire systems.

One of the most important properties of the Currents' Physical Component is their effect on the three-phase rms value of the load current. Each of them increases this value independently from each other.

$$||\boldsymbol{i}|| = \sqrt{||\boldsymbol{i}_{Ca}||^2 + ||\boldsymbol{i}_{Cr}||^2 + ||\boldsymbol{i}_{Cs}||^2 + ||\boldsymbol{i}_{G}||^2 + ||\boldsymbol{i}^{n}_{Cu}||^2 + ||\boldsymbol{i}^{p}_{Cu}||^2 + ||\boldsymbol{i}^{z}_{Cu}||^2}\,. \quad (5)$$

It is because all these Components are mutually orthogonal.

The property (5) results directly in the power equation of three-phase loads supplied in four-wire systems with nonsinusoidal and asymmetrical voltage.

$$S^2 = P_C^2 + Q_C^2 + D_{Cs}^2 + D_G^2 + D_{Cu}^{n2} + D_{Cu}^{p2} + D_{Cu}^{z2}\,. \quad (6)$$

Each of the powers in this equation is a formal product of three-phase rms values of the load voltage $||u||$ and particular Currents Physical Components $||i_x||$. The active power PC in this equation can be lower than the conventional active power P by the generated active power P_G, i.e., the active power of all harmonics that transfer the energy from the load back to the supply source, namely

$$P_C = P - P_G\,. \quad (7)$$

3. "SCHOOLS" OF THE POWER THEORY

The CPC-based power theory was developed when widely disseminated power theories already existed; some of them were supported with norms and standards [17, 21, 42] and new ones [46] were under development. Thus working on the CPC-based power theory it was necessary to demonstrate that the CPC concept provides better interpretation of power phenomena in electrical circuits than other existing power theories. Consequently, in parallel to the development of the CPC concept, critical analysis of other concepts was needed. This analysis has demonstrated that in the presence of the supply voltage distortion and asymmetry, most of power theories erroneously interpret physical phenomena in electrical circuits and do not provide right fundamentals

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for their compensation. The very practical question – **How can the difference between the apparent power S and the active power P be reduced by a compensator?** was not appropriately answered by these theories.

The development of the power theory with nonsinusoidal voltages and currents was initiated by Steinmetz's observation [1] that the power equation $P^2 + Q^2 = S^2$ in a circuit with an arc bulb is not fulfiled. Questions on the reactive power definition and the form of the power equation have occurred. Apparently trivial, these questions have appeared to be extremely difficult. Attempts aimed at finding answers are continued even now. Unsuprisingly the number of papers on these issues probably exceeds one thousand. The questions: - **"why can the apparent power S be higher than the active power P and what phenomena in the load are responsible for this inequality?"** are very fundamental for power systems performance. The very practical question: – **"how can the difference between the apparent power S and the active power P be reduced by a compensator?"** follows the previous cognitive questions. The right answer to this question is crucial for developing methods of the power factor improvement.

Over the years a lot of answers to these questions have arisen. Scientists involved in studies on the power theory development established a number of "schools", centered around dominating concepts. In such a way several schools of power theory were created. The most known are power theories established by Budeanu [7], Fryze [9], Shepherd, Zakikhani [18], Kusters and Moore [20], CPC by Czarnecki [23], FBD Method by Depenbrock [34], Instantaneous Reactive Power p-q Theory by Akagi and Nabae [24], Conservative Power Theory (CPT) by Tenti [46]. There were also concepts that are difficult to be classified as belonging to some of these "schools" [15, 16, 19, 30, 36, 43, 45, 49, 50], but which affected our present comprehension of power related phenomena in electrical circuits. Some concepts on powers supported by norms or standards are taught at universities and disseminated in papers and academic textbooks.

Unfortunately, in spite of all these research efforts, the existing power theories in the presence of the supply voltage distortion were not capable by 1984 of describing power properties of even a simple RL load as shown in Fig. 1.

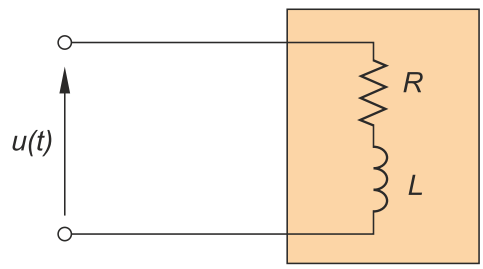

Fig. 1. RL load.

Moreover, these theories did not provide fundamentals needed for calculating parameters of a compensator for the power factor λ of such a load improvement. This problem was eventually solved [23, 32, 56] with the implementation of the CPC-based power theory.

The development of the CPC-based power theory with other concepts of this theory in the background is illustrated in a diagram shown in Fig. 2. It shows times when particular new concepts were reported as well as their impact upon the CPC development.

This diagram emphasizes the fact that it was not possible to develop power theory of three-phase circuits before power properties of single-phase circuits were comprehended. The concepts of the active, reactive and scattered currents in single-phase circuits had to be developed before that.

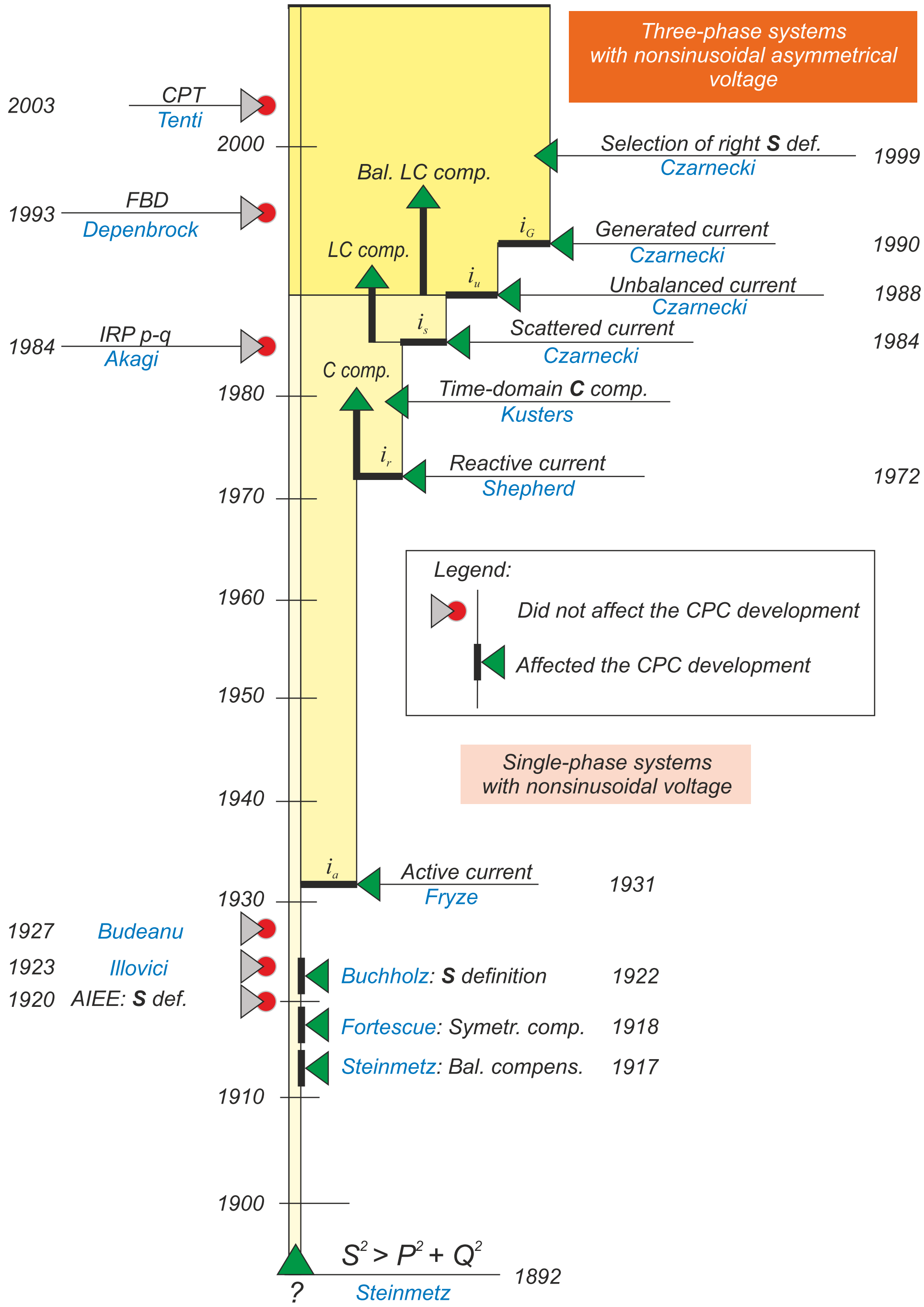

Fig. 2. Diagram of the CPC – based power theory development as referred to other power theories development.

4. TIME AND FREQUENCY DOMAINS

Two main approaches to the power theory development have competed almost all the time. These approaches were related to the question: **Should power properties be interpreted and described in the time-domain or rather in the frequency-domain, i.e., with the use of harmonic concept?** The first power theory, developed by Budeanu [7], was formulated in the frequency-domain. In Fryze's opinion, harmonics do not exist as physical entities, however, so that harmonics should not be used for describing such an important physical phenomenon as the energy transfer. Metrological availability of harmonics was also important in Fryze's argumentation. In times of Budeanu and Fryze, before digital signal processing was developed, only the rms (crms) value of harmonics, but not their phase could be measured with analog filters. It was almost impossible to measure harmonics phase. Currently, measurement/calculation of both the rms value and the phase angle of the voltage and current harmonics, bearing in mind complex rms and crms values, can be easily done by commonly available digital meters.

In Fryze's opinion [9, 25], the energy flow should be described exclusively in the time-domain. He supported this opinion with results of analysis of energy flow in the circuit shown in Fig. 3. In this circuit, supplied from a DC voltage source, a periodic switch closes the circuit.

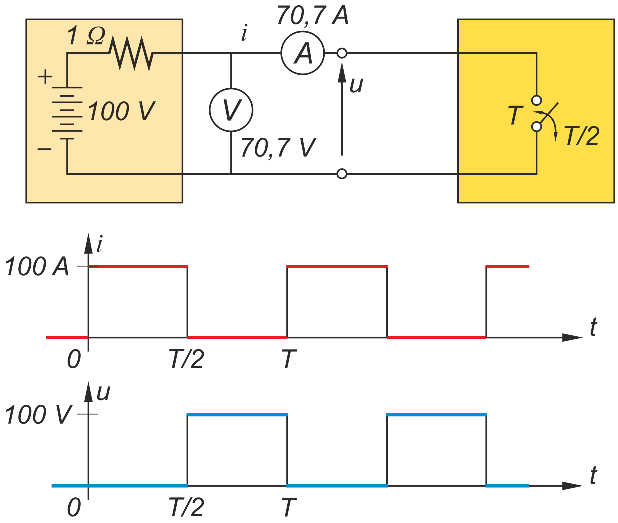

Fig. 3. A circuit with a periodic switch.

The voltage and current at the load terminals can be expressed in terms of Fourier series

$$u(t) = U_0 + \sqrt{2}\sum_{n=1}^{\infty} U_n \cos(n\omega_1 t + \alpha_n) = \sum_{n=0}^{\infty} u_n \ , \tag{8}$$

$$i(t) = I_0 + \sqrt{2}\sum_{n=1}^{\infty} I_n \cos(n\omega_1 t + \beta_n) = \sum_{n=0}^{\infty} i_n \ . \tag{9}$$

The instantaneous power, i.e. the rate of the energy $W(t)$ flow between the supply source and the load, is equal to the product of the load voltage and current, namely

$$p(t) = \frac{dW(t)}{dt} = u(t)\, i(t) = \sum_{r=0}^{\infty} u_r \sum_{s=0}^{\infty} i_s = \sum_{n=0}^{\infty} S_n \cos(n\omega_1 t + \psi_n) \ . \tag{10}$$

Thus in the frequency-domain, using harmonics, very little can be concluded on the flow of the energy. It looks as if this flow is composed of infinite number of oscillating components. On the other hand, in the time-domain it is evident that apart from points of discontinuity,

$$p(t) = \frac{dW(t)}{dt} = u(t)\, i(t) = 0 \ , \tag{11}$$

so that there is no flow of the energy in this circuit. Time-domain in the Fryze's opinion is definitely superior over the frequency-domain.

In spite of that opinion, the CPC-based power theory is formulated in the frequency-domain for two reasons. First of all, the reactive current

$$i_{\rm r}(t) \stackrel{\rm df}{=} \sqrt{2}\,{\rm Re}\sum_{n\in N} jB_n \boldsymbol{U}_n e^{jn\omega_1 t} \ , \tag{12}$$

has a clear physical interpretation only in the frequency-domain as an effect of the phase-shift between the voltage and current harmonics, at non-zero susceptance B_n. This current contributes to an increase of the load current rms value, but its interpretation in the time-domain is not known.

Next, the load current can contain the scattered current

$$i_{\rm s}(t) \stackrel{\rm df}{=} (G_0 - G_{\rm e})U_0 + \sqrt{2}\,{\rm Re}\sum_{n\in N} (G_n - G_{\rm e})\boldsymbol{U}_n e^{jn\omega_1 t} \ , \tag{13}$$

which also contributes to the load current rms value and is interpreted in the frequency-domain as the effect of the load conductance G_n change with the harmonic order n. The physical phenomenon of this change is in frequency-domain by nature. Is unlikely that this phenomenon could be explained without use of the harmonic.

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5. INSTANTANEOUS AND AVERAGING APPROACHES

Scientists who study electric powers faced also a question: **should powers be defined as instantaneous entities or as entities calculated by averaging over the period of the voltage and current variability?**

The most fundamental power, the rate of the energy flow between the supply source and the load, i.e., the instantaneous power, $p(t) = dW(t)/dt = u(t)\ i(t)$, is defined as instantaneous quantity. Therefore, should the whole power theory be based in instantaneous quantities? Affirmative answer to this question was a starting point for the Instantaneous Reactive Power p-q Theory, developed [24] by Nabae, Kanazawa and Akagi in 1984.

One could ask a question, however: **could the power properties of electrical loads be really determined instantaneously, in the event of single-phase loads, just observing two samples of instantaneous values of the voltage and current, as shown in Fig. 4?**

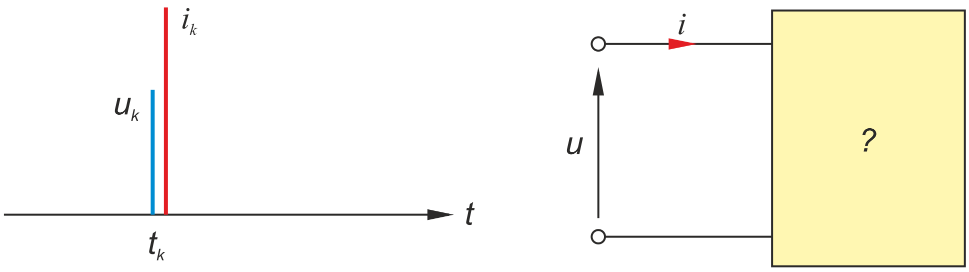

Fig. 4. Unknown load and a pair of voltage-current samples at its terminal.

The answer is, of course, negative. This is not possible. As it is illustrated in Fig. 5, a resistor, inductor or a capacitor can have mutually identical pairs of the voltage-current samples.

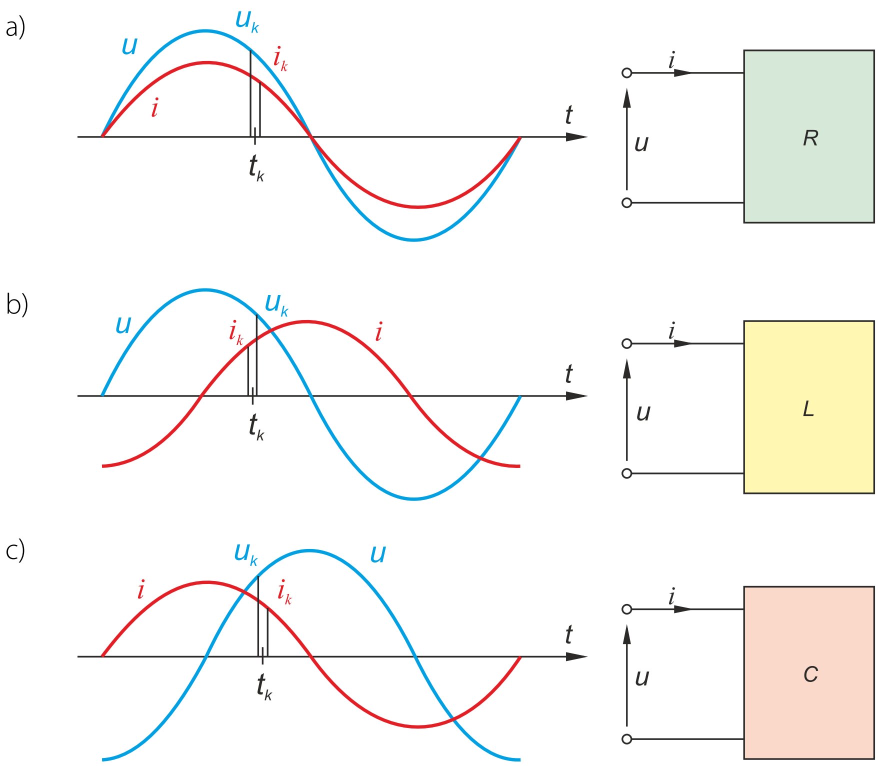

Fig. 5. Three different loads with identical pairs of the voltage-current samples.

In general, an infinite number of different loads can have such identical pairs of samples. No conclusion on power properties of the load can be drawn without observation of the voltage and current samples over the whole period of their variability.

Samples of voltages and currents of a three-phase load are used in the Instantaneous Reactive Power (IRP) p-q Theory for calculating instantaneous active and reactive powers p and q. According to the Authors of the IRP p-q Theory, the load is at each instant of time specified by a pair of p and q powers, which enables generation of the reference signal for a switching compensator control. Unfortunately, as it was demonstrated in [47] such a pair (p, q) of instantaneous powers does not allow for identification of power properties of the load. Thus, instantaneous compensation is not possible.

Instantaneous powers p and q are defined as some algebraic forms of the supply voltage and the load current. Observing some features of these powers we are not able to conclude whether these features are caused by the load current or by the supply voltage [62]. This can lead to erroneous control [53, 55] of switching compensators. Consequently, the instantaneous approach to power theory is not a right approach. Moreover, the state of distribution systems is specified in terms of quantities obtained by averaging in the period of the voltage variability. The rms values of voltages and currents, active, reactive or apparent powers, power factor, symmetrical components, rms values of harmonics, distortion and asymmetry coefficients are obtained by averaging. Therefore, the CPC-based power theory was founded on the averaging approach.

6. APPARENT POWER IN THREE-PHASE SYSTEMS

The electric energy is transferred and used mainly in three-phase systems, therefore, power properties of three-phase circuits are the very core of the power theory. Because of that a lot of effort [3, 8, 10, 12, 13, 14, 25, 26, 51] was devoted for describing power properties of three-phase circuits in the presence of the voltage distortion and asymmetry. Power properties of single-phase systems are important because without their explanation it would not be possible to comprehend power properties of three-phase circuits.

There were two major obstacles for the development of the power theory of three-phase circuits. The lack of the right interpretation of these properties in single-phase circuits was the first of them. The lack of the right definition of the apparent power S in three-phase system was the second obstacle.

The American Institute of Electrical Engineers (AIEE) suggested [4] in 1920 two definitions of the apparent power for three-phase circuits. The first one, known as the arithmetical apparent power, has the form

$$S = U_{\mathrm{R}} I_{\mathrm{R}} + U_{\mathrm{S}} I_{\mathrm{S}} + U_{\mathrm{T}} I_{\mathrm{T}} = S_{\mathrm{A}} \quad . \tag{14}$$

The second definition, known as geometrical apparent power, has the form

$$S = \sqrt{P^2 + Q^2} = S_{\mathrm{G}} \quad . \tag{15}$$

The debate on these two definitions in the twenties [11] was inconclusive and both definitions were supported by the IEEE Standard Dictionary of Electrical and Electronic Terms [42] and affected the electrical engineering community and studies on power theory.

In 1922 Buchholz suggested [5], without due justification, however, a different definition of the apparent power

$$S = \sqrt{U_{\mathrm{R}}^2 + U_{\mathrm{S}}^2 + U_{\mathrm{T}}^2}\,\sqrt{I_{\mathrm{R}}^2 + I_{\mathrm{S}}^2 + I_{\mathrm{T}}^2} = S_{\mathrm{B}} \quad . \tag{16}$$

However this definition was not known well in the electrical engineering community. It would be to the same extent justified by the fact that in circuits with sinusoidal and symmetrical voltages and currents these three definitions result in the same numerical value of the apparent power. Nonetheless, studies on power properties of three-phase circuits were dominated by geometrical definition.

In paper [28], where for the first time the concept of CPC was applied to three-phase circuits with nonsinusoidal and asymmetrical currents, the apparent power was defined in a different way, namely as

$$S = ||\boldsymbol{u}||\,||\boldsymbol{i}|| \quad . \tag{17}$$

Thus it was defined as product of three-phase rms values of the load voltages and currents. The quantity referred to as **"three-phase rms value"** was also defined along with its physical interpretation in that paper. This new definition in systems with sinusoidal voltages and currents is identical with the Buchholz's definition. The question: **which definition S_A, S_G or S_B is right?** has still not been answered.

The apparent power S is not a physical quantity, i.e., it does not have any physical interpretation. It is only a conventional quantity. Nonetheless, it should provide right fundamentals for the power factor λ calculation. Its value is related to the loss of energy at its delivery to a customer, who can be financially charged with its cost.

For example, when the load has the structure and parameters as shown in Fig. 6 and assuming that transformer is ideal, then the apparent power S calculated according to definitions (14), (15) i (16) is, respectively, equal to

$$S_A = 351 \text{ kVA},\ S_G = 304 \text{ kVA},\ S_B = 430 \text{ kVA},$$

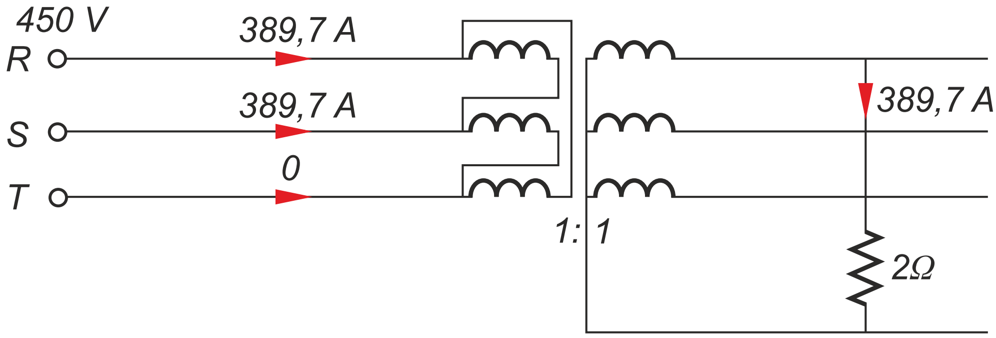

Fig. 6. Unbalanced three-phase load.

while the power factor

$$\lambda_A = \frac{P}{S_A} = 0.86,\quad \lambda_G = \frac{P}{S_G} = 1,\quad \lambda_B = \frac{P}{S_B} = 0.71\,.$$

The question which of these three definitions of the apparent power provides right value of the power factor was studied in [44]. It was concluded that the right value of the power factor is obtained when the apparent power is calculated according to the Buchholtz' definition. Power factor calculated using arithmetical and geometrical definitions can have a wrong value.

7. COMPENSATION

Compensation which as a goal has the power factor improvement, i,e., an increase in the effectiveness of energy transfer, is the most important practical application of the power theory. The technical tools for that i.e. compensators can be classified as

- Reactive compensators,
- Switching compensators,
- Hybrid compensators, composed of reactive and the switching ones.

The first compensator for balancing three-phase loads was the reactive compensator developed by Steinmetz [2] in 1917 and known as the Steinmetz' circuit. It was a reactive compensator developed for circuits with symmetrical, but sinusoidal supply voltage.

Calculation of LC parameters of a reactive compensator can be regarded as an optimization problem and any power theory is not needed for that. The optimization result does not contribute to our comprehension of compensation, though. Moreover, optimization procedures, due to the amount of calculation needed, are not appropriate when the compensator should have adaptive properties. The same goes for compensation of fast varying loads. More appropriate for that are algebraic methods, i.e., meaning calculation of LC parameters of the compensator using algebraic formulae. Such formulae cannot be developed without sufficiently advanced power theory, though. Therefore, the progress in compensation is closely related to the progress in the power theory development.

The first concepts of power theory as suggested by Budeanu and by Fryze did not create fundamentals for compensation. In the presence of the supply voltage distortion these theories did not provide any method for calculation of even such a simple compensator as a shunt capacitor.

The first step in this direction was taken in 1972 by Shepherd and Zakikhani [18]. They suggested a new power theory and a new definition of the reactive current. This definition, in the frequency-domain, made calculation of an optimal capacitance C_{opt} possible, the capacitance that minimizes the rms value of the reactive current. The phase-shift angle between the voltage and current harmonics was needed for this optimal capacitance calculation, though. This was beyond the capability of the measurement technology of that time, which was based on analog harmonic filters. Measurement of phase angle of a harmonic was very difficult and inaccurate.

Kusters and Moore suggested [20] a method of calculation of the optimal capacitance C_{opt} in the time-domain. It was a major progress, important to such a degree that the International Elektrotechnical Committee (ICE) recommended [21] power definitions and method suggested for use in electrical engineering. Unfortunately, it has occurred [22] that the suggested method in common industrial situations does not allow for calculation of the optimal capacitor of a compensator. Moreover, capacitive compensation in circuits with distorted supply voltage can enhance the waveform distortion and should be avoided.

Fundamentals of reactive compensation in single-phase circuit with nonsinusoidal supply voltage were eventually developed [23, 56] with the implementation of the CPC – based power theory in 1984. It transpired that the reactive current can be compensated entirely by a shunt reactive compensator, while the scattered current is not affected by such a compensator. Consequently, unity power factor cannot be achieved by a shunt reactive compensator. This is possible [32] by a series-shunt compensator.

A method of synthesis of balancing reactive compensators for three-phase circuits with nonsinusoidal supply voltage was developed [29, 35, 60] in the frame of the CPC – power theory in 1989. It was applied [38, 40] for control of an adaptive hybrid compensator, composed of a reactive and a switching compensator. The CPC concept can be used [33, 35] for minimization of the rms value of the reactive and unbalanced currents with a reactive compensator of complexity reduced to two reactive elements per compensator's branch. It can be also applied [68] for synthesis of reactive compensator for three-phase circuits with loads supplied by a four-wire line.

Switching compensators are commonly known as "active power filters". These are not active devices and they are not filters, but compensators, though. Such compensators are very often controlled by algorithms based on the Instantaneous Reactive Power (IRP) p-q Theory. These algorithms, when developed using the IRP p-q Theory, in the presence of the supply voltage distortion and asymmetry generate erroneous [53, 55] control signals for the compensator control.

Control of a compensator with algorithms based on the CPC-base power theory [48, 54] has two advantages. It enables to control of adaptive hybrid [38, 40] compensators, composed of reactive and switching compensators. Moreover, it enables [52] for a free selection of a Currents' Physical Component that should be compensated and to what degree. This feature could be beneficial when compensation resources, i.e., the available power of the compensator are confined. This is important particularly at compensation of very high power loads, such as, for example, ac arc furnaces. Compensation of the major part of the unbalanced and reactive currents requires reactive compensators, because limited switching power of transistors, needed for construction of a switching compensator, could be not sufficient [73]. Hybrid compensators can be needed for such loads.

8. MAIN FEATURES OF OTHER POWER THEORIES

Budeanu's power theory was developed in 1927 [7] by a professor of Bucharest University, Romania. It is formulated in the frequency-domain. It was the first attempt of describing power properties of a single-phase load supplied with nonsinusoidal voltage. It is probably the most disseminated power theory, supported also by IEEE Standard Dictionary of Electrical and Electronic Terms [42]. Its correctness was challenged in 1987 in the paper [27], where it was shown that

- There is no physical phenomenon in the circuit associated with the reactive power Q defined by Budeanu.
- There is no relation between the distortion power D defined by Budeanu and mutual distortion of the load voltage and current.
- There is no relation between the load power factor and the Budeanu's reactive power Q.

Fryze's power theory was developed in 1931 [9] by a professor of Lwów University, Poland. It was formulated in the time-domain with averaging over the period of the voltage variability. It introduced the concept of the active current; decomposition of the load current, rather than power; and separation of the current components which are mutually orthogonal. It introduced a concept of a reactive current, but without providing any physical interpretation, other than it is a useless current. It did not contribute to research into compensation.

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Shepherd and Zakikhani's power theory was developed in 1972 by professors of Bradford University, England. It was formulated [18] in the frequency-domain. It introduced a new definition of the reactive current $i_r(t)$. This definition created, for the first time, fundamentals for calculating capacitance, called optimum capacitance C_{opt}, which in the presence of voltage harmonics increases the power factor λ to its maximum value. Unfortunately, power equation lacked the most important active power quantity, namely the active power P. **Kusters and Moore's power theory** was developed [20] in 1980 in the National Research Council (NRC) of Canada. It was formulated in the time-domain. It solved the problem of calculation of the optimal capacitance C_{opt} of a shunt capacitive compensator without any need of measurement of the phase-shift between the load voltage and current harmonics. It was recommended [21] by the International Electrotechnical Committee (ICE). As it was shown in [22] the method was valid provided that the supply source is ideal, i.e., its voltage is not affected by the compensator.

The Instantaneous Reactive Power p-q Theory developed [24] in Tokyo Institute of Technology in 1984 by Nabae, Akagi and Kanazawa and generalized by Peng and Lai [39]. It was developed in the time-domain without averaging. In fact, it is a power theory of three-phase circuits and provides fundamentals for switching compensators control, provided that the supply voltage is sinusoidal and symmetrical, however. It interprets power phenomena in electrical circuits erroneously [47, 62].

The CPC-based power theory developed by the author of this paper was formulated in the frequency-domain. Its development was illustrated with the diagram shown in Fig. 2. It is currently the most advanced power theory of single and three-phase circuit with nonsinusoidal and asymmetrical voltages. It provides explanation for all physical phenomena that affect the supply current increase at the energy transfer. The CPC-based power theory provides fundamentals for synthesis of reactive compensators and for control of switching compensators. It can be used as a starting point for studies on tariffs for energy when it is delivered to customers in the presence of harmonics and asymmetry. Moreover, it provides a starting point for studies on power properties in circuits with non-periodic voltages and currents [71].

FBD (Fryze-Buchholtz-Depenbrock) Method developed [34] by Prof. Depenbrock from Bochum University, Germany in 1993. It is formulated in the time-domain. It generalizes the Fryze's power theory to three-phase circuits with the apparent power definition according to Buchholtz. It shares all advantages and disadvantages with the Fryze's power theory.

Conservative Power Theory (CPT) developed [46] by Prof. Tenti and co-workers at Padua University, Italy, in 2003. It is formulated in the time-domain. Although it follows Fryze's idea of the load current decomposition into orthogonal components, it has to a large degree [65, 72] features of the Budeanu's power theory. Current components in the CPT are not associated, apart from the active current, with any physical phenomena in the circuit. It does not provide theoretical fundamentals for reactive compensators synthesis.

BIBLIOGRAPHY

[1] Ch.P. Steinmetz, "Does phase displacement occur in the current of electric arcs?" (in German), *ETZ*, 587, 1892.

[2] Ch.P. Steinmetz, "Theory and calculation of electrical apparatur," *McGraw-Hill Book Comp.,* New York, 1917.

[3] W.V. Lyon, "Reactive power and unbalanced circuits", *Electrical World*, pp. 1417–1420, 1920.

[4] A.I.E.E. Committee, "Apparent power in three-phase systems", *Transactions of A.I.E.E.,* Vol. 39, pp. 1450–1455, 1920.

[5] F. Buchholz, "Die Drehstromscheinleistung bei Unglaichmaβger Belastung der drei Zweige," *Licht und Kraft,* pp. 9–11, 1922.

[6] M.A. Illovici, "Definition et mesure de la puissance et de l'energie reactives", *Bull. Soc. Franc. Electriciens*, 1925.

[7] C.I. Budeanu, "Puissances reactives et fictives," *Institut Romain de l'Energie*, Bucharest, 1927.

[8] E. Weber, "Die elektrische Leistung in allgemeinen Wechselstromkreis", *ETZ*, p. 1547, 1929.

[9] S. Fryze, "Active, reactive and apparent power in circuts with nonsinusoidal voltages and currents", *Przegląd Elektrotechniczny,* z. 7, pp. 193–203, z. 8, pp. 225–234, 1931, z. 22, pp. 673–676, 1932.

[10] W. Quade, "Über Wechselstrome mit beliebiger Kurvenform in Dreiphasensystemen", *Archiv fur Elektr.*, vol. 28, pp. 798–809, 1934.

[11] H.L. Curtis, F.B. Silsbee, "Definitions of power and related quantities", *Transactions of AIEE*, Vol. 54, pp. 394–404, 1935.

[12] F. Emde, "Scheinleistung eines nicht sinusformigen Drehstromes", *Elektrotechnik und Machinen*, pp. 555–565, 1937.

[13] I. Rosenzweig, "Symbolic multidimensional approach to analysis of multiphase systems" (in Polish) *Czasopismo Techniczne*, pp. 6–11, 1939.

[14] V.N. Nedelcu, "Die enheitliche Leistungstheorie der unsymmetrischen mehrwelligen Mehrphasensysteme", *ETZ-A,* no. 5, pp. 153–157, 1963.

[15] M. Depenbrock, "Blind- und Scheinleistung in einphasing gespeisten Netzwerken", *ETZ-A,*, Bd. 85, F.13, pp. 385–391, 1964.

[16] Z. Nowomiejski, Z. Cichowska, "Unbalanced three-phase systems" (in Polish), Scientific Letters of Gliwice Univ. of Techno-logy, *ELEKTRYKA*, no. 17, pp. 25–76, 1964.

[17] Wechselstromgrossen, 303–310, 1972.

[18] W. Shepherd, P. Zakikhani, "Suggested definition of reactive power for nonsinusoidal systems," *Proc. IEE*, vol. 119, no. 9, pp. 1361–1362, 1972.

[19] M. Depenbrock, "Wirk- und Blindleistung," *ETG-Fachtagung "Blindleistung",* Aachen 1979.

[20] N.L. Kusters, W.J.M. Moore, "On the definition of reactive power under nonsinusoidal conditions," *IEEE Trans. Pow. Appl. Syst*., vol. PAS-99, no. 3, pp. 1845–1854, 1980.

[21] International Electrotechnical Commission, (1979), Techn. Committee No. 25, Working Group 7, Report: "Reactive power and distortion power", doc. no. 25, 113 (Secr.).

[22] L.S. Czarnecki, "Additional discussion to "On the definition of reactive power under nonsinusoidal conditions," *IEEE Trans. on Power and Syst*., vol. PAS-102, no. 4, pp. 1023–1024, 1983.

[23] L.S. Czarnecki, "Considerations on the reactive power in nonsinusoidal situations," *IEEE Trans. on Instr. and Measurements*, vol. IM-34, no. 3, pp. 399–404, 1984.

[24] H. Akagi, Y. Kanazawa, A. Nabae, "Instantaneous reactive power compensators comprising switching devices without Energy Storage Components," *IEEE Trans. Ind. Appl,* vol. IA-20, no. 3, pp. 625–630, 1984.

[25] S. Fryze, "Theorethical and physical fundamentals for the active, reactive and apparemt power definitions in multi-phase systems with distorted voltages and currents" (in Polish), Zeszyty Naukowe Politechniki Śląskiej *ELEKTRYKA*, nr 100, pp. 29–46, post-humos publ., 1985.

[26] K. Koch, "Bestimmung von Groβen in Mehr-Leitr Systemen", *ETZ Archiv*, vol. 8, no. 10, pp. 313–318, 1986.

[27] L.S. Czarnecki, "What is wrong with the Budeanu concept of reactive and distortion powers and why it should be aban-doned," *IEEE Trans. Instr. Meas.*, vol. IM-36, No. 3, pp. 834–837, 1987.

[28] L.S. Czarnecki, "Orthogonal decomposition of the current in a three-phase non-linear asymmetrical circuit with nonsinu-soidal voltage," *IEEE Trans. Instr. Meas*., vol. IM-37, no. 1, pp. 30–34, 1988.

[29] L.S. Czarnecki, "Reactive and unbalanced currents compensation in three-phase circuits under nonsinusoidal conditions," *IEEE Trans. IM, vol. Instr. Meas*., IM-38, no. 3, pp. 754–459, 1989.

[30] A.E. Emanuel, "Powers in nonsinusoidal situations. A review of definitions and physical meanings", *IEEE Transations on Pow. De*l, vol. 5, no. 3, pp. 1377–1389, 1990.

[31] L.S. Czarnecki, T. Swietlicki, "Powers in nonsinusoidal networks, their analysis, interpretation and measurement," *IEEE Trans. Instr. Measur*., vol. Instr. Meas., IM-39, no. 2, 340–344, 1990.

[32] L.S. Czarnecki, "Scattered and reactive current, voltage, and power in circuits with nonsinusoidal waveforms and their compensation," *IEEE Trans. Instr. Meas*., vol. 40, no. 3, pp. 563–567, 1991.

[33] L.S. Czarnecki, "Minimization of unbalanced and reactive currents in three-phase asymmetrical circuits with nonsinusoidal voltage," *Proc. IEE* Pt. B, 139, no. 4, pp. 347–354, 1992.

[34] M. Depenbrock, "The FBD-method, a generalized applicable tool for analyzing power relations" *IEEE Trans*. on Power Del., vol. 8, no. 2, pp. 381–387, 1993.

[35] L.S. Czarnecki, "Dynamic, power quality oriented approach to theory and compensation of asymmetrical systems under nonsinusoidal conditions", *European Trans. on Electric Power, ETEP,* vol. 5, pp. 347–358, Sept./Oct. 1994.

[36] G. Superti-Furga, "Searching for generalization of the reactive power – a proposal", *European Transactions on Electrical Power Engineering, ETEP*, vol. 4, no. 5, pp. 411–420, 1994.

[37] L.S. Czarnecki, "Power theory of electric circuits: common data base of power related phenomena and properties", *Europ. Trans. on Electrical Power, ETEP,* vol. 4, no. 5, pp. 491–408, 1994.

[38] L.S. Czarnecki, S.M. Hsu, G. Chen, "Adaptive balancing compensator," *IEEE Trans. on Power Delivery*, vol. 10, no. 3, pp. 1663–1669, July 1995.

[39] F.Z. Peng; J.S. Lai, "Generalized instantaneous reactive power theory for three-phase power systems," *IEEE Transactions on Instrum. and Meas.*, vol. 45, no. 1, pp. 293, 297, Feb. 1996.

[40] L.S. Czarnecki, G. Chen, Z. Staroszczyk, "Application of running quantities for control of adaptive hybrid compensator," *European Trans. on Electrical Power, ETEP*, vol. 6, no. 5, pp. 337–344, Sept./Oct. 1996.

[41] L.S. Czarnecki, "Budeanu and Fryze: two frameworks for Interpreting power properties of circuits with nonsinusoidal voltages and currents," *Archiv fur Elektrot*., 81, no. 2, pp. 5–15, 1997.

[42] The New IEEE Standard Dictionary of Electrical and Electronics *Terms, IEEE* Inc., New York, 1997.

[43] W. le Roux, J.D. vanWyk, "Correspondence and difference between the FBD and Czarnecki current decomposition methods for linear loads", *European Transactions on Electrical Power Engineering, ETEP*, vol. 8, no. 5, pp. 329–336, 1998.

[44] L.S. Czarnecki, "Energy flow and power phenomena in electrical circuits: illusions and reality," A*rchiv fur Elektrotechnik*, 82, no. 4, pp. 10–15, 1999.

[45] Z. Cekareski, A.E. Emanuel, "Pointing Vector and the power quality of electric energy", *Europ. Trans. on Electrical Power Eng., ETEP,* vol. 11, no. 6, pp. 375–382, 2001.

[46] P. Tenti, P. Mattavelli, "A time-domain approach to power terms definitions under non-sinusoidal conditions," *6th Int. Workshop on Power Definitions and Measurement under Non-Sinusoidal Conditions*, Milan, Italy, 2003.

[47] L.S. Czarnecki, "On some misinterpretations of the Instantaneous Reactive Power p-q Theory," I*EEE Trans. on Power Electronics*, vol. 19, no. 3, pp. 828–836, 2004.

[48] A. Firlit, "Current's Physical Components Theory and p-q Power Theory in the control of the three-phase shunt active power filter," *7th Int. Workshop on Power Definitions and Meas. under Non-Sinusoidal Conditions,* Cagliari, Italy, 2006.

[49] L.S. Czarnecki, "Could power properties of three-phase systems be described in terms of the Poynting Vector?" *IEEE Trans. on Power Delivery*, 21, no. 1, 339–344, 2006.

[50] P.E. Sutherland, "On the definition of power in an electrical system", *IEEE Trans. on Pow. Del.*, vol. 22, pp. 1100–1107, 2007.

[51] W.G. Morsi, M.E. El-Hawary, "Defining power components in nonsinusoidal unbalanced polyphase systems: the issues", *IEEE Trans. on Power Delivery,* vol. 22, no. 4, pp. 2428–2438, 2007.

[52] H.L. Ginn, G. Chen, "Switching compensator control strategy based on CPC power theory", Proc. of the International School of Nonsinusoidal Currents and Compensation, (*ISNCC*), Łagów 2008.

[53] L.S. Czarnecki, "Effect of supply voltage harmonics on IRP-based switching compensator control," *IEEE Trans. on Power Electronic*s, vol. 24, no. 2, pp. 483–488, 2009.

[54] L.F. Monteneiro, J.L. Alfonso, J.G. Pinto, E.M. Watanabe, H. Akagi, M. Aredes, "Compensation algorithms based on the p-q and CPC theories for switching compensators in micro-grids", P*roc. of COBEP 09 Power Electronics Conference*, Brazilian DOI: 10.1109/ COCEP.2009.5347593, pp. 32–40, 2009.

[55] L.S. Czarnecki, "Effect of supply voltage asymmetry on IRP p-q - based switching compensator control," *IET Proc. on Power Electronics*, vol. 3, no. 1, pp. 11–17, 2010.

[56] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 2. Current's Physical Components and compensation in single-phase time-invariant loads," *Automatyka, Elektryka, Zakłócenia*, www.elektro-innowacje.pl, vol. 1, nr 2, pp. 71–79, 2010.

[57] L.S. Czarnecki, "Recollections on Professor Fryze and reflections on his place in the power theory development" *Przegląd Elektrotechniczny,* R. 87, nr 1, pp. 123–128, 2011.

[58] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 3. Current's Physical Components and compensation in single-phase with Harmonic Generating Loads (HGL)," *Automatyka, Elektryka, Zakłócenia*, www.elektro-innowacje.pl, vol. 1, nr 3, pp. 44–54, 2011.

[59] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 4. Current's Physical Components and compensation three-phase unbalanced systems in sinusoidal conditions," *Automatyka, Elektryka, Zakłócenia,* www.elektro-innowacje.pl, vol. 1, nr 4, pp. 57–65, 2011.

[60] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 6. Compensation of three-phase unbalanced systems in sinusoidal conditions," www.elektro-innowacje.pl, *Automatyka, Elektryka, Zakłócenia,* vol. 6, no. 4, pp. 51–57, 2011.

[61] L.S. Czarnecki, "Working, reflected and detrimental active powers," *IET on Generation, Transmission and Distribution*, vol. 6, no. 3, pp. 223–239, 2012.

[62] L.S. Czarnecki, "Constraints of the Instantaneous Reactive Power p-q Theory", *IET Power Electr.*, vol. 7, no. 9, pp. 2201–2208, 2014.

[63] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 6. Powers in Linear Three-Phase Systems with Neutral Conductor", www.elektro-innowacje.pl, *Automatyka, Elektryka, Zakłócenia*, nr 1, pp. 48–58, 2014.

[64] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 7. Strategies of switching compensator control", www.elektro-innowacje.pl, *Automatyka, Elektryka, Zakłócenia*, vol. 4, nr 2, pp. 44–54, 2014.

[65] L.S. Czarnecki, "Critical comments on the Conservative Power Theory (CPT)", Proc. of Int. School on Nonsinusoidal Currents and Compensation, (*ISNCC*), Łagów 2015.

[66] L.S. Czarnecki, P. Bhattarai, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 8. "Powers and reactive compensation at asymmetrical supply voltage", www.elektro-innowacje.pl, *Automatyka, Elektryka, Zakłócenia*, 2015.

[67] L.S. Czarnecki, "Powers and compensation in circuits with nosinusoidal voltages and currents, Part 9. Misinterpretation of power properties of electrical circuits", www.elektro-innowacje.pl, *Automatyka, Elektryka, Zakłócenia*, vol. 6, nr 3(21), pp. 6–17, 2015.

[68] L.S. Czarnecki, P.M. Haley, "Unbalanced power in four-wire systems and its reactive compensation", *IEEE Trans. on Power Delivery*, vol. 30, no. 1, pp. 53–63, Feb. 2015.

[69] L.S. Czarnecki, P.M. Haley, "Power properties of four-wire systems at nonsinusoidal supply voltage," *IEEE Trans. on Power Delivery*, vol. 31, no. 2, pp. 513–521, 2016.

[70] L.S. Czarnecki, P. Bhattarai, "Currents' Physical Components of unbalanced three-phase LTI loads at asymmetrical nonsinu-soidal supply voltage", Proc. of Int. School on Nonsinusoidal Currents and Compensation, (*ISNCC*), Łagów 2015.

[71] A.R. Izaguirre, M.E. Macias, F. Martell, "Accurate CPC power analysis under extreme EAF's distortion conditions", Proc. of Int. School on Nonsinusoidal Currents and Compensation, (*SNCC*), Łagów 2015.

[72] L.S. Czarnecki, "What is wrong with the Conservative Power Theory (CPT)", Proc. of Int. Conf. on Applied and Theoretical Electr., *ICATE*, *Craiova,* Romania 2016.

[73] L.S. Czarnecki, P. Bhattarai, "A method of calculation of LC parameters of balancing compensators for AC arc furnaces", to be printed in *IEEE Trans. on Power Delivery*, 2016.

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