Letter to the Editor:

Comments on "Apparent Power – a Misleading Quantity in the Non-Sinusoidal Power Theory: Are all Non-Sinusoidal Power Theories Doomed to Fail?"

L. S. Czarnecki

Abstract

It is shown in this comment that recent development in the power theory of systems with non-sinusoidal waveforms contradicts the conclusions presented in the paper "Apparent Power - a Misleading Quantity in the Non-Sinusoidal Power Theory: Are all Non-Sinusoidal Power Theories Doomed to Fail?" published by P. S. Filipski in ***ETEP*** *3 (1993), no. 1, pp. 21 – 26. That paper deforms the history of the power theory development and its present state. Moreover, the notion of 'power theory' should not be associated with a particular power equation, but be comprehended as a knowledge base on power properties of electric circuits, revealed with various approaches. The comment discusses also the notion of 'apparent power' as a conventional quantity.*

1 Introduction

A collective effort of innumerable scientists and engineers has resulted in a comprehension of energy related phenomena in non-sinusoidal single-, and three-phase, linear, non-linear, balanced, and unbalanced systems. Main questions as regards to improving power factor in such system have been answered. Various compensators for non-sinusoidal systems have been studied or built. Therefore, the question: "Are all Non-Sinusoidal Power Theories Doomed to Fail?" asked in the title of paper [C1] seems to be equivalent to questions like these:

- Was this collective effort on the power theory development in vain?
- Is our interpretation of energy flow phenomena erroneous?
- Are the methods of compensation as developed with existing power theory incorrect?
- Will not the compensators built for improving the power factor work?

Fortunately, even if we still argue over some interpretations or definitions; even if compensation methods still could be improved; even if still some questions are not answered, the effort, exemplified at least partially with [C2 – C24], aimed at developing the power theory of systems with non-sinusoidal waveforms, was not in vain. The power theory of non-sinusoidal systems was developed and it answers effectively a lot of theoretical and technical questions.

If the power theory is in such a good shape, why it was disapproved, however, in the paper [C1]? The arguments presented in that paper may look apparently convincing, particularly that the paper does not refer to results published recently, but only to very old publications, often out of date now. An unprepared reader could accept these arguments with a harm for his understanding the power properties of non-sinusoidal systems. Therefore, this question should be answered.

This answer is made difficult because paper [C1] deals mainly with apparent problems, or out of date now. It claims, for example, that a new dispute on definition of the reactive power revived recently, and "new definitions of reactive power appear with increased frequency". This frequency is not too high, if only one suggestion of a new definition appeared [C14] in the last decade, however. Moreover, even this one definition, after discussion in [C15], does not seem to supersede the definition suggested by *Shepherd* and *Zakikhani* [C2] more than 20 years ago.

A lot of terms used in the paper discussed are not defined or vague which makes author's reasoning difficult to follow. Terms like 'RMS' or 'amplitude' are well known. Namely, for a periodic quantity $x(t)$, the RMS value $\|x\|$ is defined as

$$\|x\| := \sqrt{\frac{1}{T}\int_0^T x^2(t)\,\mathrm{d}t}\,,$$

while 'amplitude' means the maximum instantaneous value of a sinusoidal oscillation. What does "RMS amplitude" mean, however? Also, what it is "reactive instantaneous VA"? What it is "apparent VA"? What it is "AC quadrature component"? What it is "in-phase (to what?) component"? All these terms are not defined in the paper [C1] nor they are in a common use in electrical engineering. One could expect that a scientific paper is written with well defined or at least commonly known terms, but not with an unclear jargon.

2 Comments on the History of the Power Theory Development

The account of how new definitions of reactive power were introduced and how power equations were developed as presented in section 2 of paper [C1] does not comply with the published results. Majority of them were not developed as suggested.

The study of particular power equations shows that their authors started, usually, with a decomposition of the source current into components of a particular importance in their authors opinion. As a consequence, these authors' opinion on the importance of particular components of the current has split the development of the power theory into a number of paths and differentiated equations compiled below.

To emphasize differences in the form of these equations, they are presented here for the same circuit category, namely, for a single-phase linear load supplied from an ideal source of non-sinusoidal voltage

$$u(t) = \Sigma U_n \cos(n\omega_1 t). \tag{C1}$$

- *Fryze*'s equation was developed starting from the following decomposition of the source current

  $$i = i_a + i_b, \tag{C2}$$

  where symbol i_a denotes the active current which is indispensable for the active power transmission and which is of the voltage $u(t)$ waveform, while current i_b does not contribute to the active power transmission.

- *Shepherd* and *Zakikhani*'s [C2] equation was developed starting with decomposition of the source current

  $$i = \Sigma I_n \cos(n\omega_1 t - \varphi_n) \tag{C3}$$

  into the current 'in phase' with the voltage, namely

  $$i_R := \Sigma I_n \cos\varphi_n \cos(n\omega_1 t) \tag{C4}$$

  and the reactive current

  $$i_r := \Sigma I_n \sin\varphi_n \sin(n\omega_1 t) \tag{C5}$$

  such that

  $$i = i_R + i_r. \tag{C6}$$

- *Depenbrock*'s [C3] equation was developed starting with separation of the fundamental harmonics u_1 and i_1 from the voltage and current

  $$u = u_1 + u_k, \quad i = i_1 + i_k, \tag{C7}$$

  with

  $$u_k := u - u_1, \quad i_k := i - i_1. \tag{C8}$$

- *Kusters* and *Moore*'s [C5] equation was developed starting from the decomposition of the source current into the active current i_a, the capacitive reactive current i_{qc} which can be compensated with a shunt capacitor that increases the power factor to its maximum value, and a current not affected by such a capacitor i_{qcr}, namely

  $$i = i_a + i_{qc} + i_{qcr}. \tag{C9}$$

  The currents i_{qc} and i_{qcr} were defined as

  $$i_{qc} := \frac{(i,\dot{u})}{\|\dot{u}\|^2}\dot{u}, \quad i_{qcr} := i - i_a - i_{qc}, \tag{C10}$$

  respectively, where $\dot{u} := (d/dt)\,u$; the bars $\|$ denote the RMS value, and $(i, \dot{u})$ denotes the scalar product of the current and the voltage derivative $\dot{u}$.

- *Czarnecki*'s [C10] equation was developed starting from the decomposition of the source current i into the active current i_a, the reactive current i_r, and the scattered current i_s which occurs if the load conductance G_n changes with the harmonic order n around an equivalent conductance G_e, namely

  $$i = i_a + i_s + i_r \tag{C11}$$

  where

  $$i_s := \sqrt{2}\,\mathrm{Re}\sum(G_n - G_e)\,\underline{U}e^{jn\omega_1 t}, \tag{C12}$$

  and $\underline{U}_n := U_n e^{j\alpha_n}$ is the complex RMS value of the n-order voltage harmonic.

All current components in eqs. (C2), (C6), (C7), (C9) or (C11) are proved to be orthogonal, so that the RMS value of the current $\|i\|$ can be expressed in terms of the RMS values of these components. For example, the RMS value of the source current $\|i\|$ can be expressed in terms of RMS values of the components i_a, i_{qc}, and i_{qcr} as follows:

$$\|i\|^2 = \|i_a\|^2 + \|i_{qc}\|^2 + \|i_{qcr}\|^2. \tag{13}$$

Multiplying such equation for the source current RMS value with the square of the supply voltage RMS value, $\|u\|^2$, *Kusters* and *Moore*'s power equation

$$S^2 = P^2 + Q_c^2 + Q_{cr}^2 \tag{14}$$

can be obtained, with

$$S := \|u\|\|i\|, \quad P = \|u\|\|i_a\|,$$

$$Q_c := \|u\|\|i_{qc}\|, \quad Q_{cr} := \|u\|\|i_{qcr}\|. \tag{15}$$

The apparent power S in this equation and the powers Q_c and Q are conventional quantities, without any physical interpretation, like the apparent power S in a sinusoidal situation. This procedure, valid also at developing power equations suggested by *Fryze*, *Shepherd* and *Zakikhani*, *Depenbrock*, or *Czarnecki*, has nothing in common with the alleged approach as described in section 2 of [C1] at introducing new powers. Moreover, the equations obtained in this procedure do not contain any "meaningless component" $(REST)_n$ as suggested in section 3. Thus these two Sections deform substantially the history of the development of the power theory of non-sinusoidal systems.

The same relates to the assertion terminated with eq. (21). Orthogonality of current components in eqs. (C2), (C4), (C7), (C9), or (C11) is not an assumption as suggested in the paper [C1], section 5. It is a proven property of these components. Also, it is a proven property of these components, but not an "assumption that RMS values of the current must be equal to the geometric sum of RMS values of all current components" as suggested in the paper [C1].

3 Why the Apparent Power S is not a Misleading Quantity?

The apparent power is qualified as a "misleading quantity" in [C1] because it is considered there as a physical quantity, while it is only a conventional quantity. A usefulness of the convention is the only needed justification for such a quantity. In the case of apparent power S in single-phase systems, the convention is very simple: the product of the voltage and current RMS values, $\|u\|\|i\|$, is assumed to be named 'apparent power'. Even the adjective 'apparent' emphasizes clearly, that this product does not specify any 'real' power. A conventional quantity cannot be misleading or not misleading. It can be only accepted or not accepted. Misleading seems to be rather the conclusion that only a physical interpretation of the apparent power S justifies the equation

$$S^2 = P^2 + Q^2. \tag{C16}$$

The apparent power S does not have physical interpretation, however, independently if the waveforms are sinusoidal or non-sinusoidal. There is a number of differences between power properties of systems with sinusoidal and non-sinusoidal waveforms, but the convention with regard to apparent power S is the same. Of course, if someone does not find the convention assumed for the apparent power, $S := \|u\|\|i\|$, sufficiently justified for his needs, he may abandoned it for a better one.

The concern in [C1] that eq. (C16) does not have physical interpretation with the conclusion that the apparent power is "a misleading quantity in non-sinusoidal power theory" is only a pseudo-problem. Problems of this kind can be generated even further: The active power P is a mean value of the instantaneous power, while Q is the amplitude of its oscillating component. Thus could we add up such quite different entities? With such doubts and questions the electrical engineers might not be confused with the apparent power, but rather with apparent problems.

Dealing with the apparent power in three-phase systems one could be confused, however, not because of the claim that apparent power is a misleading quantity, but because there are different conventions as to definition of the this power. Some conventions have the form

$$S := S_R + S_S + S_T \tag{C17}$$

$$S := \sqrt{3\left(S_R^2 + S_S^2 + S_T^2\right)}, \tag{C18}$$

where S_R, S_S, and S_T are the apparent powers of phases R, S, and T. Moreover, it can be defined directly with line voltages and currents RMS values, namely

$$S := \|u\|\|i\| = \sqrt{U_R^2 + U_S^2 + U_T^2}\sqrt{I_R^2 + I_S^2 + I_T^2}. \tag{C19}$$

It may be only a matter of a study and discussions which convention could be the most appropriate for a specific situation, but not which of them has a physical interpretation. Observe, that the need for conventions goes even deeper. Even if we agree to accept, for example, the convention expressed with definition (C19), the choice of the reference point for measuring voltages U_R, U_S, and U_T will be still a matter of convention.

The paper [C1] does not contribute anything, however, to a discussion regarding advantages or disadvantages of particular conventions (see eqs. (C17), (C18), (C19)), mainly because the various definitions of the apparent powers S are analyzed in section 4 of [C1] in terms of quantities which have nothing in common with power properties of non-sinusoidal systems, namely in terms of *Budeanu*'s reactive and distortion powers, Q_B and D. It was demonstrated long ago [C13] that quantity Q_B, defined by *Budeanu*, cannot be considered as a reactive power. Also, the 'distortion power' D has nothing in common with waveform distortion. Comparison of various definitions of the apparent power in terms of quantities Q_B and D does not provide any information on the relation of these powers to the power properties of the system. Also the "three-dimensional representation of apparent powers", drawn in coordinates P, Q_B and D as shown in Fig. 3, does not provide any information on advantages or disadvantages of particular conventions.

4 Power 'Theory' or 'Theories'?

The notion of the 'power theory' with respect to systems with non-sinusoidal waveforms does not have any distinct meaning. It is used in [C1] in a plural form. It is suggested in the Abstract, for example, that: "... several new power theories have been proposed recently".

It is true, that at first *Fryze*'s approach was set against *Budeanu*'s approach as a different power theory, especially, before the equivalence of the time-domain and the frequency-domain was fully understood. This was reflected also in titles of publications [C4] and [C9]. It seems, however, that just *Fryze* has terminated this opposition when he expressed [C8] *Budeanu*'s quantities Q_B and D (defined originally in the frequency-domain) according to his approach, i. e., in the time-domain. Doing it, he elevated the importance of power properties of the system over their mathematical description. Unfortunately, he fell down into a trap of *Budeanu*'s approach, since the powers Q_B and D have occurred later to have no relation to power phenomena in non-sinusoidal systems.

It seems that after more than seventy years of research, having so many items of knowledge on power properties of non-sinusoidal systems, many approaches to their description, and a variety of conclusions regarding compensation, we should comprehend the notion of the 'power theory' as a knowledge base relative to energy flow phenomena. Power theory comprises sets of equations that provide fundamentals for a physical interpretation of energy flow and general concepts aimed at improving power properties of circuits with non-sinusoidal voltages and currents. This is a conclusion which could be drawn from a study of various attempts aimed at power theory formulation. Mathematical fundamentals of the theory are accompanied, usually, with some interpretations and more or less advanced concepts of compensation, though the earliest concepts of the power theory formulation have not suggested any method of the power factor improvement.

Thus we should not look at each equation which reveals some information on power properties, or on each conclusion or definition as on an item of a different power theory. As long as such an equation or a conclusion is not proved to be erroneous, it is an item of the same power theory. Each scientist or engineer who has developed such an equation or has drawn such a conclusion is a contributor to the power theory. Its formulation can be considered as a dynamic process of enrichment, successive improvements and corrections.

Equations, definitions and models developed in the power theory have occurred as a trade off and a compromise between mathematical complexity needed for description of power phenomena and usefulness of the power theory as a practical tool for engineers. It is easy, usually, to disapprove a compromise without suggesting any alternative, as it is in the case of the paper discussed.

5 Is the Power Theory of Non-Sinusoidal Systems Needed?

In the section 5 of [C1] the author discusses the need of the power theory development in terms of several questions: "do we need...?". He asserts that we do not need it, and declares our lack of interest in "new power theories". But who are "we"? One could ask if *Shepherd, Depenbrock, Koch, Ferrero, Superti Furga, Nabae, Kusters, Moore, Czarnecki, Willems, van Wyk, Sun* and many others who have developed the power theory belong to the set { we }. A reader of paper [C1] may observe also that just these, not needed, "new power theories" have enabled the author to conclude in the Abstract: "Traditional non-sinusoidal power theory does not reflect properly the energetic relations in non-sinusoidal systems".

Development of power theory can be considered as an attempt to answer the question: why the current RMS value in a circuit with non-sinusoidal waveforms may be higher than that needed for the active power transmission and how to reduce it? A need for the answer of such a question could be of a practical nature or purely intellectual. Just this intellectual curiosity shapes us as human beings. It shapes also our technology. Of course, it is also natural that only some of us ask such questions. Others are not involved. A lack of knowledge in the subject may follow the lack of interest, however. As a consequence, an author that declares the lack of interest in the subject may have very little to convey to a reader. He may also convey erroneous ideas, like this in paper [C1] that power theory is irrelevant for methods of compensation. The author of paper [C1] seems to be wholly unaware that the concept of instantaneous imaginary power introduced by *Akagi* and *Nabae* [C7] provides the control algorithm for active power filters; that the question "can the power factor under non-sinusoidal conditions be improved to unity value?" was answered positively in [C21] only after the power theory was sufficiently developed. The same relates to methods aimed at improving the power factor in unbalanced three-phase systems with non-sinusoidal voltages [C16, C23] which benefit from the development in the power theory of three-phase systems as presented in [C12].

6 Conclusions

The assertion that the apparent power S is a "misleading quantity" in the paper [C1] is not supported with any convincing reasoning. It was formulated because the author failed to observe that apparent power is a conventional quantity. Only evaluation and justification of particular conventions could be a matter of discussion.

Various assertions in the paper [C1] of a general nature, such as the need of the power theory development, its relation to compensation, or answers to general questions as that in the paper title "are all non-sinusoidal power theories doomed to fail?" could be formulated based only on a personal deep expertise, i. e., the knowledge of the subject and its literature. The paper [C1] does not show, however, that its author is well acquainted with the history of the power theory development, with recently published results, and with compensation-related problems. Thus the general assertions on the power theory are not supported with a sufficient expertise which could expected if such substantial assertions are formulated.

References

[C1] *Filipski, P. S.:* Apparent Power – a Misleading Quantity in the Non-Sinusoidal Power Theory: Are all Non-Sinusoidal Power Theories Doomed to Fail? ETEP Eur. Trans. on Electr. Power Engng. 3 (1993) no. 1, pp. 21–26

[C2] *Shepherd, W.; Zakikhani, P.:* Suggested definition of reactive power for non-sinusoidal systems. Proc. IEE 119 (1972) no. 9, pp. 1361–1362

[C3] *Depenbrock, M.:* Wirk- und Blindleistungen periodischer Ströme in Ein- und Mehrphasensystemen mit periodischen Spannungen beliebiger Kurvenformen. ETG-Fachber. 6 (Blindleistung), Offenbach · Berlin/Germany: vde-verlag, 1979, pp. 1–31

[C4] *Nowomiejski, Z.:* Generalized theory of electric power. Arch. f. Elektrotech. 63 (1981) pp. 177–182

[C5] *Kusters, N. L.; Moore, W. J. M.:* On the definition of reactive power under non-sinusoidal conditions. IEEE Trans. on Power Appar. a. Syst. PAS-99 (1980) pp. 1845–1854

[C6] *Fodor, G.; Tevan, G.:* Power and compensation in networks in periodic state. Arch. f. Elektrotech. 65 (1982) pp. 27–40

[C7] *Akagi, H.; Kanazawa, Y.; Nabae, E.:* Instantaneous reactive power compensators comprising switching devices without energy storage components. IEEE Trans. on Ind. Appl. IA-20 (1984) no. 3, pp. 625–630

[C8] *Fryze, S.:* Theoretical and physical fundamentals of active, reactive and apparent powers in unbalanced multiphase systems with non-sinusoidal voltages and currents (in Polish). Sci. Letters Elektryka no. 100, Gliwice Tech. Univ. (Posthumous publ. for Prof. Fryze 100th Birthday Celebration), (1985) pp. 29–46

[C9] *Czarnecki, L.:* Power theories of periodic non-sinusoidal systems, Rozprawy Elektrotechniczne 31 (1985) no. 3–4, pp. 659–685

[C10] *Czarnecki, L.:* Considerations on the reactive power in non-sinusoidal situations. IEEE Trans on Instr. Meas. IM-34 (1985) no. 3, pp. 399–404

[C11] *Koch, K.:* Bestimmung von Größen in Mehr-Leiter-Systemen. etzArchiv 8 (1986) no. 10, pp. 313–318

[C12] *Czarnecki, L. S.:* Orthogonal decomposition of the currents in a 3-phase nonlinear asymmetrical circuit with non-sinusoidal voltage source. IEEE Trans. Instrumentat. a. Meas. IM-37 (1987) no. 1, pp. 30–34

[C13] *Czarnecki, L. S.:* What is wrong with the *Budeanu* concept of reactive and distortion powers and why it should be abandoned. IEEE Trans. Instrumentat. a. Meas. IM-36 (1987) no 3, pp. 834–837

[C14] *Enslin, J. H. R.; van Wyk, J. D.:* Measurement and compensation of fictitious power under non-sinusoidal voltage and current conditions. IEEE Trans. Instrumentat. a. Meas. IM-37 (1988) no. 3, pp. 403–408

[C15] *Czarnecki, L. S.:* Comments on 'Measurement and compensation of fictitious power under non-sinusoidal voltage and current conditions'. IEEE Trans. Instrumentat. a. Meas. IM-38 (1989) no. 3, pp. 839–841

[C16] *Czarnecki, L. S.:* Reactive and unbalanced currents compensation in three-phase circuits under non-sinusoidal conditions. IEEE Trans. Instrumentat. a. Meas. IM-38 (1989) no. 3, pp. 754–759

[C17] *Gyarfas, J.; Rapant, S.:* Theory and Practice of Energy Measurement of Non-sinusoidal and Asymmetrical Currents and Voltages. ETEP Eur. Trans. on Electr. Power Engng. 1 (1991) no. 3, pp. 159–164

[C18] *Sun, S. Q.; Kiyokawa, H.:* Decomposition of voltage, current and power. IEE Proc. B-138 (1991), no. 1, pp. 35–39

[C19] *Sun, S. Q.; Huang, S:* On the meaning of non-sinusoidal active current. IEEE Trans. Instrumentat. a. Meas. IM-40 (1991) no. 1, pp. 36–38

[C20] *Ferrero, A.; Superti Furga, G.:* A new approach to the definition of power components in three-phase systems under non-sinusoidal conditions. IEEE Trans. Instrumentat. a. Meas. IM-40 (1991) no. 3, pp. 568–577

[C21] *Czarnecki, L. S.:* Scattered and reactive current, voltage and power in circuits with non-sinusoidal waveforms and their compensation, IEEE Trans. Instr. Meas. IM-40 (1991) no. 3, pp. 363–367

[C22] *Czarnecki, L. S.:* Distortion power in systems with non-sinusoidal voltage. IEE Proc. B-139 (1992) no. 3, pp. 276–280

[C23] *Willems, J.:* Current Compensation in Three-Phase Power Systems. ETEP Eur. Trans. on Electr. Power Engng. 3 (1993) no. 1, pp. 61–66

[C24] *Andria, G.; Salvatore, L.; Savino, M.; Trotta, A.:* Measurements of Power and Current Components in Unbalanced and Distorted Three-Phase Systems. ETEP Eur. Trans. on Electr. Power Engng. 3 (1993) no. 1, pp. 75–83

"Letter" received on September 21, 1993

(Professor *Leszek S. Czarnecki*, Dept. of Electrical and Computer Engineering, Louisiana State University, 102 Electrical Engineering Building, Baton Rouge, Louisiana, LA 70803-5901/USA, T +1504/388-5241, Fax +1504/388-5200)