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Essay on Troubles of Electrical Engineers with Physics

Esej o kłopotach elektryków z fizyką

Abstract: *This Essay shows that, although electrical engineering has emanated from physics, nonetheless it is sometimes with this physics in conflict. Some properties of electrical circuits are from the physics perspective erroneously interpreted or thought that some objects exist physically. It refers to some electrical powers and harmonic components. There are even some alleged physical phenomena. This conflict of electrical engineering with physics is subjective, however, an electrical engineer can understand and interpret physical properties of electrical circuits in his own way.*

Streszczenie: *Ten esej pokazuje, że jakkolwiek elektrotechnika jest technologicznie zorientowaną emanacją fizyki, to pozostaje niekiedy z tą fizyką w konflikcie. Pewne właściwości obwodów elektrycznych bywają z perspektywy fizyki błędnie interpretowane lub też pewnym obiektom przypisuje się istnienie fizyczne. Dotyczy to pewnych mocy elektrycznych oraz składowych harmonicznych. W przekonaniu pewnych elektryków istnieją nawet zjawiska fizyczne, które w istocie są jedynie domniemane. Ten konflikt elektrotechniki z fizyką ma oczywiście charakter subiektywny, każdy elektryk może rozumieć fizyczne cechy obwodu w sposób odmienny.*

Keywords: *physical properties, conflict, physical phenomena, harmonic components*

Słowa kluczowe: *fizyczne cechy obwodu, konflikt elektrotechniki, składowe harmoniczne*

1. INTRODUCTION

A moment of reflection on the subject of this essay leads to the conclusion that these 'troubles' are probably of subjective nature. My problem with physics is not necessarily identical with the problem of my colleague the electrical engineer. Each of us may interpret physical phenomena in a different way. Each of us may hold a different view on what may be treated as physical objects. This may not be related to quantum-level physics, since the physicists themselves display interpretational discrepancies. Electrical engineers are products of electrical engineering, and this subject is based on classical physics.

On account of the subjectivity of these difficulties with physics, this article will not be written in an impersonal form (which might relate to all electricians). My personal views will be stated here based upon my personal observations, experience, and reflections.

The justification for the subject of this essay may be demonstrated by considering the title of one of the leading power engineering journals, namely IEEE Transactions on Power Delivery. From the physics viewpoint this title is incorrect, since power systems do not deliver power to the consumers; they deliver energy. Power is the speed with which energy is transferred; it is energy and not speed that is supplied to the load.

This lack of precision in the Transactions title is usually ignored and appropriated as a kind of engineering jargon. Maybe it is so. If "power" and "energy" are used interchangeably, nobody will die. Such a lack of accuracy in terminology might be fatal in medicine. However, in electrical engineering this occasional lack of precision in physical terms is not a fundamental problem. Electrical engineering evolved from physics and physics constitutes the basis of electrical engineering. The conformance with physics guarantees the correctness of electrical engineering. That is why each discrepancy between electrical engineering and physics should be closely observed and pointed out, since it may lead to mistakes. This essay will demonstrate several case examples.

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2. PHYSICS AND POWER THEORY

More than a century of research into power theory for circuits with non-sinusoidal waveforms is a very good example of electrical engineers' troubles with physics. This research was initiated by Steinmetz in 1892. He observed [1] that in a circuit containing an arc lamp, the active power P, the reactive power Q and the apparent power S do not fulfil the power equation.

$$P^2 + Q^2 = S^2 \,. \tag{1}$$

The investigations led to the emergence of nine different schools of Power Theory. These schools define powers and describe the energy properties of electrical circuits in widely divergent and often mutually contradictory ways. These schools are identified by the surnames of their founders, i.e., Budeanu [2], Fryze [3], Shepherd and Zakikhani [4], Kusters and Moore [5], Nabay and Akagi [6], Depenbrock [7], Tenti [8] and Czarnecki [9], [10]. Most of these researchers have been distinguished by the highest honorary title of Fellow IEEE for their contribution to power theory. However, the author of the current essay was able to show in several articles [11], [12], [13], [14], [15], and in a book [10], that these theories describe the energy properties of electrical circuits incorrectly. The surprising thing is that all these theories are valid from the mathematical standpoint. At the same time, the physical phenomena accompanying the transfer of energy in electrical circuits are wrongly described or interpreted.

The complexity of physical phenomena and their interpretation may be attested by the following episode in power theory development. In 1927, Budeanu introduced [2] the concept of reactive power Q_B and distortion power D. These concepts functioned for several decades in power theory, they were included in the IEEE Standard [16]. Only after 60 years from the date of introduction of this theory, I showed [11] that there is no phenomenon in the electrical circuit that could be quantitatively described with Budeanu's reactive power Q_B oraz że nie istnieje and that there is no phenomenon described by distortion power D. These powers were severely criticised by Prof. Fryze [3], the grand old man of Polish electrical engineering and the honorary Member of Polish Physical Society. That is why I was dumbfounded at the news that in his last (and posthumously published) article [17], Prof.Fryze proposed new definitions for reactive power Q_B and distortion power D, The definitions were formulated differently from the mathematical point of view, but Prof. Fryze did not perceive that there were no physical phenomena in the electrical circuits that might somehow be associated with these two powers.

The energy properties of the circuits have been associated with physical phenomena (single-phase and three-phase circuits with non-sinusoidal currents) only within the framework of the power theorem based upon the concept of Currents' Physical Components (CPC). This is presented fully in article [9] and book [10].

3. PHYSICS AND HARMONIC COMPONENTS

Fourier series and harmonic components are among the principal mathematical tools used in the analysis of circuits with non-sinusoidal waveforms. The instruments for measuring the voltage/current harmonic components in power engineering systems are commercially available. The standards setting the allowable harmonic content in the voltage supply are universally known. Filters are designed and used to reduce harmonic content. Since 1984, a scientific convention known as the International Conference on Harmonics in Power Systems (ICHPS) has been organised. Therefore, it seems that electrical engineers treat harmonic components as physical objects in power systems. However, Prof. Fryze showed even back in 1931 that harmonics do not exist physically. To demonstrate this, he used a circuit presented in Fig.1. The circuit is supplied from a DC source and the load is a periodically operated switch (switch is closed for half a period T, and stays open for the remaining time).

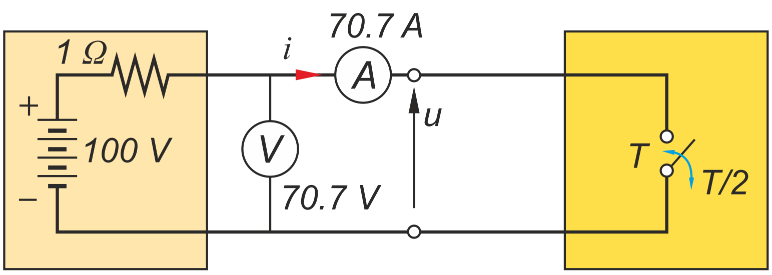

Fig. 1. Circuit with a rotary switch

The switch voltage/current waveforms are shown in Fig.2.

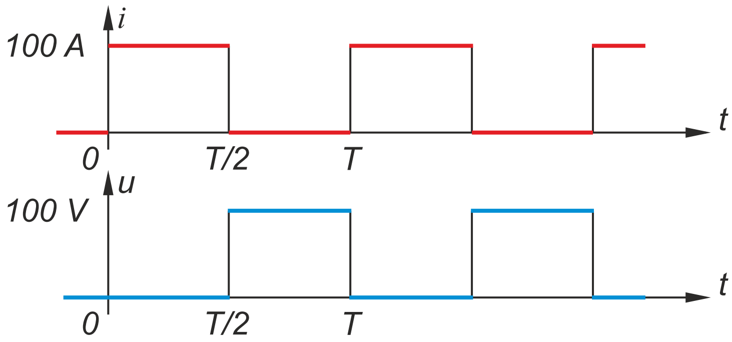

Fig. 2. Current/voltage waveforms for a switch in circuit shown in Fig.1

These waveforms may be expressed in the form of Fourier series (sum of harmonics).

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

$$i(t) = I_0 + \sqrt{2}\sum_{n=1}^{\infty} I_n \cos(n\omega_1 t + \beta_n) = \sum_{n=0}^{\infty} i_n \ . \quad (3)$$

A single non-zero harmonic of switch current

$$i_n(t) = \sqrt{2} I_n \cos(n\omega_1 t + \beta_n) \ , \quad (4)$$

is a continuous quantity from $-\infty$ to $+\infty$. So, it cannot exist when the switch is open, i.e. when switch current $i(t)$ is equal to zero. The same principle applies to non-zero harmonics of switch voltages

$$u_n(t) = \sqrt{2} U_n \cos(n\omega_1 t + \alpha_n) \ . \quad (5)$$

This cannot exist when the switch is closed and its voltage $u(t)$ is equal to zero. This means that harmonics are not physical objects, that is, they are not physically present in current and voltage. They are just mathematical objects that are used to describe analytically and approximate periodical waveforms.

Unfortunately, this observation of Prof. Fryze does not seem to have entered the minds of electrical engineers, who still treat harmonic components as physical objects. This may be exemplified by the article written by Prof. Emanuel [18]. He analyses the decrease of power factor $\lambda = P/S$, S and states that it is caused by energy oscillations between the load and supply source which originate from current/voltage harmonics. It is true that in accordance with the reasoning given in [18], when harmonics $i_n(t)$ and $u_n(t)$ are present in current and voltage, the instantaneous power of the load, i.e. the speed of energy $W(t)$ transfer from the source to the load.

$$p(t) = \frac{dW(t)}{dt} = u(t)\, i(t) \ , \quad (6)$$

contains an oscillation component

$$p_n(t) = u_n(t)\, i_n(t) \ . \quad (7)$$

This component is physically present only if harmonics $u_n(t)$ and $i_n(t)$ exist physically. But since they cannot exist physically, any energy oscillations related to them cannot exist either. We must also note that if the harmonics exist physically, then instantaneous power is the indefinite sum of oscillation components, that is,

$$p(t) = \frac{dW(t)}{dt} = u(t)\, i(t) = \sum_{n=0}^{\infty} u_n(t) \sum_{n=0}^{\infty} i_n(t) = \sum_{k=0}^{\infty} p_k(t) \ . \quad (8)$$

However, since only one of quantities at switch, i.e. either current or voltage, may be different from zero, then (and when voltage/current discontinuity points are neglected) the instantaneous power at switch is always equal to zero, because

$$p(t) = u(t)\, i(t) \equiv 0\ . \tag{9}$$

So, there are no energy oscillations. This is not obvious if we recognize that harmonic components exist physically.

4. PHYSICS AND REACTIVE POWER

The author of this essay met many colleagues (engineers and researchers both) in different countries and was able to observe that the domineering share of this community associates reactive power Q with energy oscillations between the load and the supply source. This conviction may be based upon the fact that in linear single-phase circuit (see Fig.3),

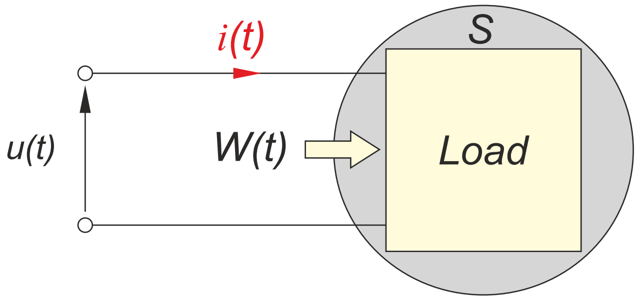

Fig. 3. Single-phase circuit

which is supplied with sinusoidal voltage and, therefore, sinusoidal current

$$u(t) = \sqrt{2}\,U\cos\omega t\ ,\quad i(t) = \sqrt{2}\,I\cos(\omega t - \varphi)\ , \tag{10}$$

instantaneous power

$$p(t) = u(t)\,i(t) = 2\,UI\cos\omega t\,\cos(\omega t - \varphi) = p_{\rm u}(t) + p_{\rm b}(t)\ , \tag{11}$$

contains an oscillating component

$$p_{\rm b}(t) = Q\sin 2\omega t\ . \tag{12}$$

The remaining component

$$p_{\rm u}(t) = P(1+\cos 2\omega t)\ , \tag{13}$$

is non-negative and represents unidirectional energy flow. The waveforms are shown in Fig.4. The amplitude of the oscillating component of instantaneous power in this circuit is equal to the reactive power Q.

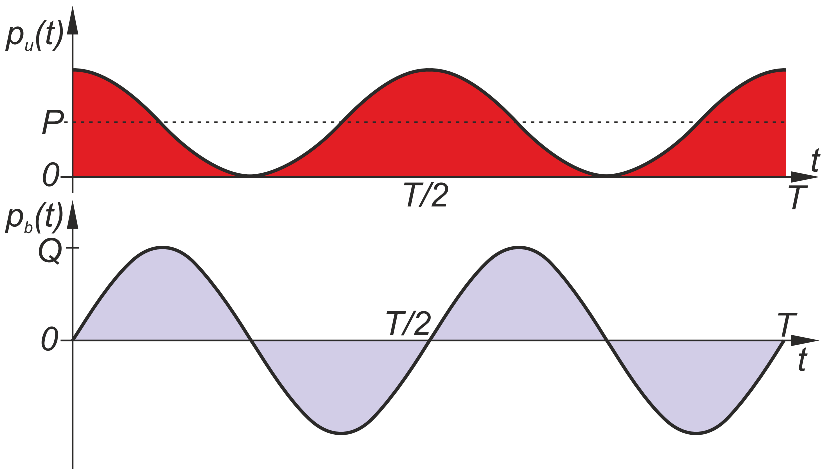

Fig. 4. Components of instantaneous power of single-phase load with sinusoidal supply voltage and sinusoidal current

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However, this property of single-phase circuits has misled the electrical engineers, since they have not observed that this property is not present in three-phase circuits. If we assume that the three-phase circuit (see Fig.3) is linear, balanced and supplied by sinusoidal voltage,

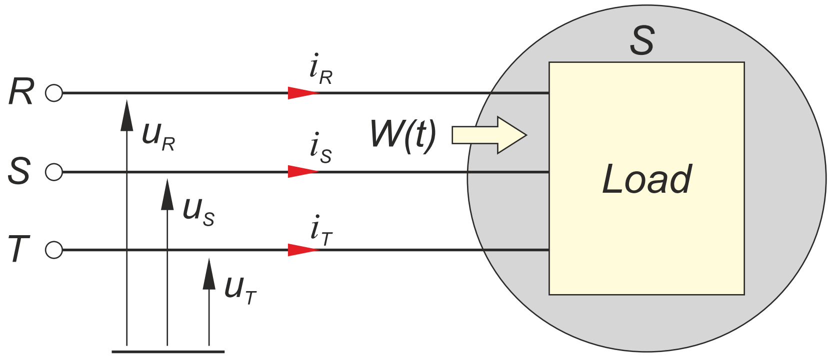

Fig. 5. Three-phase load

then its instantaneous power

$$p(t) = \frac{dW}{dt} = u_R(t)\,i_R(t) + u_S(t)\,i_S(t) + u_T(t)\,i_T(t) = 3U\,I\cos\varphi = P\ , \tag{14}$$

is constant and independent of its reactive power Q. In this circuit we have no energy oscillations between the supply source and load, which might explain the existence of reactive power Q. The reason why reactive power exists in linear circuit is the phase shift of load current in relation to the supply voltage and not alleged energy oscillations.

The reactive power emerges because of phase shift between current and voltage; however, it does not describe the phenomenon: it is the result. The shift may be caused by energy stored in electrical or magnetic fields, i.e. in resistance-reactance circuits. It may also appear in purely resistive circuits with periodically variable parameters. This means that reactive power Q does not participate in the description of physical phenomena in electrical circuits.

5. PHYSICS AND BALANCE OF POWER

The power balance principle is a most useful tool in the energy analysis of electrical circuits, it is applied in the verification of results. This principle relates to active power P and reactive power Q, the apparent power S does not fulfil the rule. It is a principle that is used in the discussion of the physical character of some energy quantities, in particular the active power P, the reactive power Q, the reactive power in accordance with Budeanu's definition Q_B, or the reactance reactive power Q_r, Qr in accordance with Tenti's definition [8]. In the last case, the fulfilment of balance principle has been even underlined in the very designation of Tenti's power theory, that is "Conservative Power Theory (CPT)"; this suggests that the reactance reactive power Q_r introduced by this theory is a physical quantity. However, we may wonder why Budeanu's reactive power Q_B, which has no relation to any physical phenomenon in the electrical circuit whatsoever, fulfils the principle of power balance.

The obscurity of the physical sense of the power balance principle may result from the fact, that it may be based on two different and more fundamental rules; one rule has a physical sense, while the other is purely mathematical. The first rule is Principle of Energy Conservation; the principle of instantaneous power $p(t)$ and active power P balance may be drawn from it. However, we cannot establish a balance of reactive powers (Q, Q_B, and Q_r.) on this principle. The balance of these three reactive powers may be derived from Tellegen's Theorem [19], which is just a mathematical and not physical property of the electrical circuits.

Principle of Energy Conservation states that if circuit consisting of K elements is electrically isolated, then its electrical energy (equal to the sum of energies of its individual elements $W_k(t)$) is constant, that is

$$\sum_{k=1}^{K} W_k(t) = Const. \tag{15}$$

From this principle, we may directly derive the rule of instantaneous power balance, that is,

$$\sum_{k=1}^{K}\frac{dW_k(t)}{dt}=\sum_{k=1}^{K}p_k(t)=0\ , \tag{16}$$

and active power balance

$$\sum_{k=1}^{K}\frac{1}{T}\int_0^T p_k(t)\,dt=\sum_{k=1}^{K}P_k=0\ . \tag{17}$$

Since the relationships of the reactive powers Q, Q_B, and Q_r with energy of electrical elements are not known, then Principle of Energy Conservation (15) does not constitute the physical basis for the principle of balance of these powers. This may be derived from Tellegen's Theorem. According to this law, if two electrical circuits consisting of K elements each are characterized by identical topology (that is the identical number of nodes connected with branches in an identical way – see Fig.6),

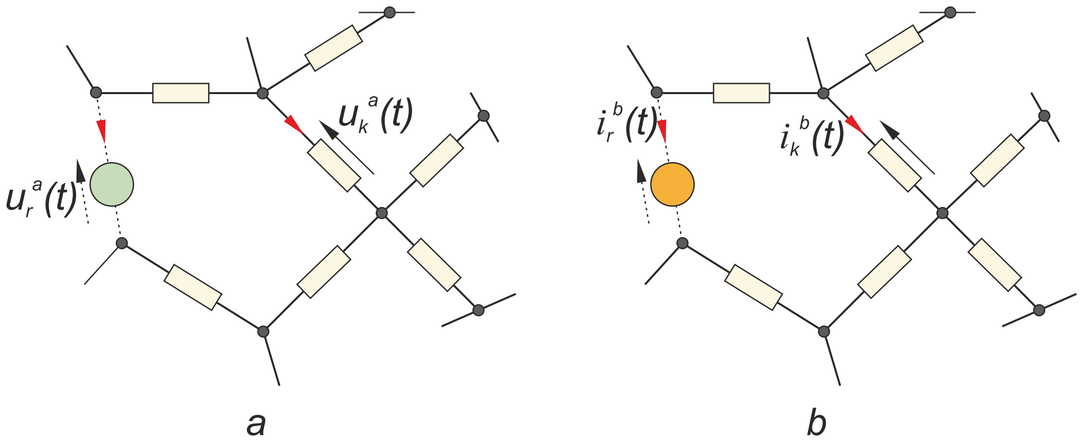

Fig. 6. Two circuits with identical topologies

then even if elements in these branches are completely different in each circuit, the sum of all K products of branch voltages of one circuit and branch currents of the other circuit is equal to zero at each time instant:

$$\sum_{k=1}^{K}u_k^{\mathrm{a}}(t)\,i_k^{\mathrm{b}}(t)\ \equiv\ 0\ . \tag{18}$$

This rule may be used to derive a principle of reactive Q conservation in the following way. If we assume that both circuits are identical where branch parameters are concerned, but source voltage and current waveforms in circuit (b) are lagging by $T/4$ in relation to the corresponding waveforms in circuit (a), that is,

$$i_k^{\mathrm{b}}(t)\ \equiv\ i_k^{\mathrm{a}}(t-\tfrac{T}{4})\ , \tag{19}$$

then from Tellegen's Theorem we may deduce that

$$\sum_{k=1}^{K}u_k^{\mathrm{a}}(t)\,i_k^{\mathrm{b}}(t)=\sum_{k=1}^{K}u_k^{\mathrm{a}}(t)\,i_k^{\mathrm{a}}(t-\tfrac{T}{4})=\sum_{k=1}^{K}u_k(t)\,i_k(t-\tfrac{T}{4})=0\ . \tag{20}$$

The reactive power Q for circuit with sinusoidal voltage and current is defined as

$$Q=UI\sin\varphi=\frac{1}{T}\int_0^T u(t)\,i(t-\tfrac{T}{4})\,dt\ , \tag{21}$$

and from Tellegen's Theorem we may infer that

$$\frac{1}{T}\int_0^T\sum_{k=1}^{K}u_k(t)\,i_k(t-\tfrac{T}{4})\,dt=\sum_{k=1}^{K}\frac{1}{T}\int_0^T u_k(t)\,i_k(t-\tfrac{T}{4})\,dt=\sum_{k=1}^{K}Q_k=0\ , \tag{22}$$

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so that the reactive power Q fulfils the balance. This is not, however, a physical property of this power, but just a mathematical feature. Reactive power Q definition (21) is not based upon any physical phenomenon, since voltage and current placed within the integral sign are observed at different time instants (shifted by $T/4$, in relation to each other). Such a product does not exist physically; it is entirely a mathematical concept.

6. ALLEGED PHYSICAL PHENOMENA

As a foundation of electrical engineering, physics is used to explain its basic laws. However, sometimes the electricians are not able to describe the energy properties of the electrical circuits in physical sense; this relates for instance to the power theory. Sometimes the opposite is true and electricians suggest the existence of some physical phenomena in order to support their concepts. The debate on instantaneous reactive power q, is a good example of this statement. This power was introduced into power theory by Nabae and Akagi in 1983 [6].

In accordance with this theory, the energy state of the load with non-sinusoidal current/voltage waveforms may be described with two instantaneous powers p and q. The first is a very well-known instantaneous power p(t), or the speed of energy flow $W(t)$; it is dubbed here with a new name here, i.e. "instantaneous active power'. The other one is instantaneous reactive power q. However, the authors of this power theory did not explain what is the physical sense of this power, and this initiated long-lasting scientific debate. Finally, in 2007, the President of IEEE Power Electronics Society Prof. Akagi did provide a physical interpretation of instantaneous reactive power q [20]. In this book the interpretation is styled in the following way:

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

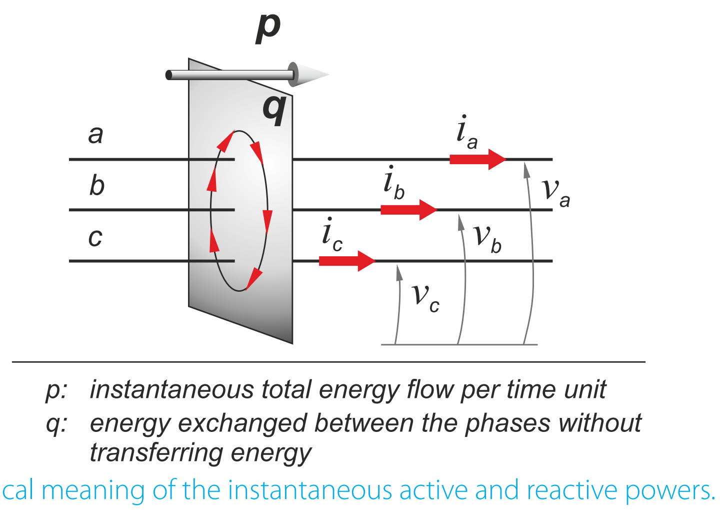

Fig. 7. Original interpretation of instantaneous reactive power q, drawing is from reference [20]

The original Akagi drawing and its caption are shown in Fig.7. To avoid ambiguity, it must be explained that in Akagi's theory, the adjective 'imaginary' is used interchangeably with 'reactive'. The same relates to adjectives „real" and „active".

According to Akagi, this interpretation is so convincing that fragments of Fig.7 with rotating power q were used for the cover of the book [20]. However, this interpretation is erroneous. Energy may flow only in a direction perpendicular to the vector of magnetic field intensity H, where the field is generated by current, which causes energy flow. Since magnetic field rotates around currents flowing in supply wires, there can be neither any whirling (as suggested by the drawing), nor energy and associated instantaneous reactive (imaginary) power q. This whirling (rotation) is only an alleged physical phenomenon.

Another supposed physical phenomenon is electromagnetic waves, used to transfer energy in power systems. This effect is described on the Internet – nowadays a significant source of information. A YouTube clip shows (very suggestively) how electromagnetic waves make it possible to transfer energy from sources to the load; this video is authenticated by two professors of power engineering.

Electromagnetic waves are obviously present in power systems. Their wavelength λ in transmission lines at 50 Hz frequency is λ = 6000 km. Since the lines are not usually impedance matched to standing loads, the electromagnetic waves emerge. They are observed as unacceptable changes in the RMS values of voltage and current along the line. Transmission lines are usually much shorter than the wavelength λ The wave effects are more evident when the line length is close to λ/4. To reduce the wave effects, compensation stations are erected along the line; as the line becomes longer, the compensation of the wave effects becomes much less effective and too expensive. Then, AC transmission is given up and DC transmission adopted instead. To avoid wave effects in long transmission lines, energy is sent via lines known as HVDC (High Voltage DC) lines. Therefore, it is not true that electromagnetic waves are used for energy transmission in power systems. These waves actually are detrimental to the transmission. The transfer of electrical energy in power systems with the help of electromagnetic waves is a sort of alleged (in the energy transmission sense) physical phenomenon, even though these waves, however harmful, exist physically.

7. CONCLUSION

This essay shows that electricians may have some problems with physics. Several examples of such issues and their underlying causes are given. At the commencement of this essay, I pointed out that these troubles might be subjective and that I would present my personal experience and observations. I will add here that I graduated from Civil Industrial Engineering Technical School (Technikum Budownictwa Przemysłowego) in Lublin. The curriculum did not contain the physics subject and that is why I was lucky enough to avoid any potential conflicts with physics.

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