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About the Rejection of Poynting Vector in Power Systems Analysis

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Summary: This article is a response to a paper presented at the sixth International Workshop on Power Definitions, a report that rejected the fact that the Poynting vector (PV) provides useful information "for academic interpretation of power properties and for practical applications of power theory". This study explains how the PV reveals the existance of power oscillations unexplained by simple mathematical models used in the basic circuit theory. It sheds light on the puzzling situation where the PV exists but does not transfer energy and also presents some examples that reinforce the usefulness of PV as a fine tool in understanding the flow and the components of electromagnetic energy.

A good scientist values criticism almost higher than friendship: no, in science criticism is the height and measure of friendship.
[Francis Crick]

1. INTRODUCTION

On December 17, 1883 John Henry Poynting submitted to Royal Society his famous paper that described and interpreted a remarkable formula:

$$\vec{\wp} = \vec{E} \times \vec{H} \qquad [\mathrm{W/m^2}] \tag{1}$$

This expression helps quantify the power density at any point in a space where the electric and magnetic field vectors $\vec{E}$ and $\vec{H}$ are known.

Recently historians discovered that Oliver Heaviside [1], an other electrical genius of the Victorian age, has developed independently a similar expression:

$$\vec{\wp} = \vec{E} \times \vec{H} + \vec{G} \tag{2}$$

where $\vec{G}$ is any arbitrary vector that has zero divergence, i.e. a vector field of closed loops (solenoidal vector).

The PV is an invaluable mathematical tool for the study of energy propagation from antennae or any kind of electrical equipment. Power loss calculations, shielding studies, penetration of electromagnetic waves through different materials, induction heating systems and many more complex designs are conveniently carried using computations or software based on PV theory. The PV was not only used in high frequency applications, but in low frequency as well. Great researchers as Joseph Slepian [2,3] and Edward Howathrone [4,5] have used the PV to analyze the energy flow through motors, or just to obtain a better grasp of the laws that govern the flow of energy through transmission lines and power equipment [3]. In the recent years the PV was used to gain a better understanding for the meaning of power definitions, with emphasis on the apparent power components [6–10]. Such efforts were met by the strong criticism of Prof. Czarnecki [11–14]. The goal of this paper is to rebut the claims made by him against PV contribution to power theory.

2. LUMPED CIRCUIT APPROACH VERSUS PV APPROACH: REVEALING THE HIDDEN OSCILLATIONS

In [13] Prof. Czarnecki referring to Figure 1a, where a balanced three-phase load is supplied by a perfectly symmetrical voltage, is asking: *"Why should I calculate the flux of the Poynting vector P over the load boundary ..... if I can calculate this rate of energy flow for my three-phase load, having supply voltage and currents, according to:*

$$\frac{dW}{dt} = p(t) = u_R i_R + u_S i_S + u_T i_T \quad ?\text{"} \tag{3}$$

The answer to his question is as follows: The above equation is hiding the true electromagnetic Phenomenon, not revealing the power density distribution in time and space. It gives only an overall result, a "macroscopic" view of the performance, i.e. the total instantaneous power $p(t)$. No information related to existing oscillations of power between the voltage source and an eventual inductance or capacitance included in the load can be explained based on the above expression.

Assuming in Figure 1a the line-to-neutral voltages:

$$\begin{aligned} u_R &= \hat{U}\, sin(\omega t) \\ u_S &= \hat{U}\, sin(\omega t - 2\pi/3) \\ u_T &= \hat{U}\, sin(\omega t + 2\pi/3) \end{aligned} \tag{4}$$

and an ideal purely inductive three-phase load, using the reactive power $Q = 3UI$ and supplied with the line currents:

$$\begin{aligned} i_R &= -\hat{I}\, cos(\omega t) \\ i_S &= -\hat{I}\, cos(\omega t - 2\pi/3) \\ i_T &= -\hat{I}\, cos(\omega t + 2\pi/3) \end{aligned} \tag{5}$$

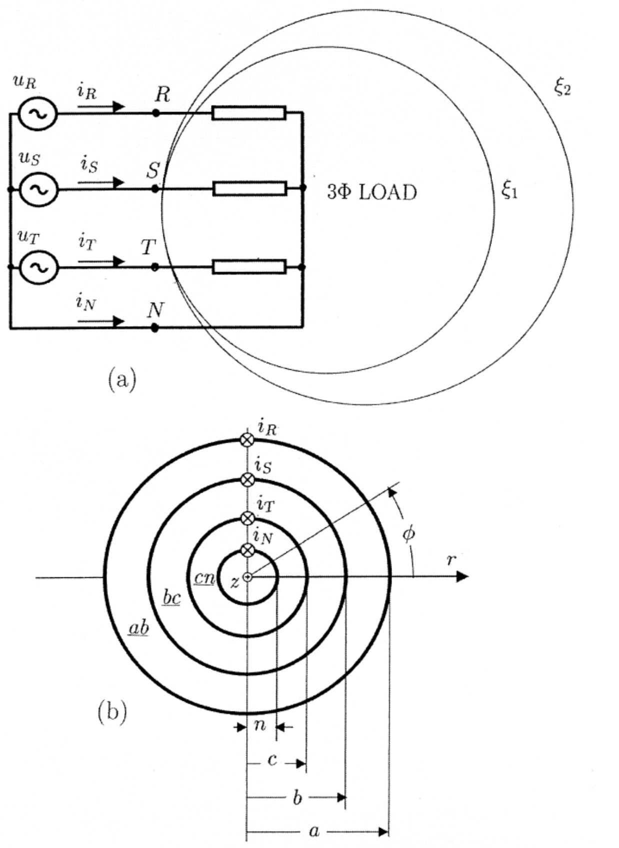

Fig. 1. Three-Phase Balanced Load Supplied by a Positive-Sequence Voltage: (a) Schematic (Hypothetical Spherical Envelopes Enclose the Load); (b) Three-Phase Line Geometry (A Three-Phase Coaxial Cable)

where $\hat{U} = \sqrt{2}U$ and $\hat{I} = \sqrt{2}I$. In this case substitution of (4) and (5) in (3) gives:

$$p(t) = u_R i_R + u_S i_S + u_T i_T = 0 \qquad (6)$$

This result may leave one puzzled when asked to explain the existence of line losses on the account of $Q = 3UI$. Prove to this interpretation is the claim made by Prof. Czarnecki in [11] that *"there is no energy oscillation between the load and source, irrelevant of the reactive power Q of the load"*. The PV approach helps solve this impasse. The geometry of the line supplying the load is presented in Figure 1b. The coaxial system was favored in this case due to the fact that the fields are perfectly confined to $r \le a$ and the computations are simple. Moreover, since the system is symmetrical the neutral current is nil and the electromagnetic waves are limited within the space $c \le r \le a$, where there are two obvious channels:

First channel ($b < r < a$): with the electric and magnetic fields:

$$\vec{E}_{ab} = \frac{u_{RS}}{ln\frac{a}{b}}\frac{1}{r}(-\vec{1}_r) \qquad (7)$$

and:

$$\vec{H}_{ab} = \frac{i_S + i_T}{2\pi r}\vec{1}_\phi = \frac{i_R}{2\pi r}(-\vec{1}_\phi) \qquad (8)$$

producing the PV:

$$\vec{\wp}_{ab} = \frac{(u_R - u_S)i_R}{2\pi \ln\frac{a}{b}}\frac{1}{r^2}\vec{1}_z \qquad (9)$$

And the second channel ($c < r < b$): with the electric and magnetic fields:

$$\vec{E}_{bc} = \frac{u_{ST}}{\ln\frac{b}{c}}\frac{1}{r}(-\vec{1}_r) \qquad (10)$$

and:

$$\vec{H}_{bc} = \frac{i_T}{2\pi r}\vec{1}_\phi \qquad (11)$$

producing the PV:

$$\vec{\wp}_{bc} = \frac{(u_S - u_T)i_T}{2\pi \ln\frac{b}{c}}\frac{1}{r^2}\vec{1}_z \qquad (12)$$

The PVs carry (or impinge) the instantaneous powers:

$$p_{ab} = -\int_a^b \vec{\wp}_{ab} \bullet 2\pi r(-\vec{1}_z) = (u_R - u_S)i_R = u_{RS}i_R \qquad (13)$$

$$p_{bc} = -\int_a^b \vec{\wp}_{bc} \bullet 2\pi r(-\vec{1}_z) = -(u_S - u_T)i_T = -u_{ST}i_T \qquad (14)$$

These results are confirmed to be correct; the total instantaneous power is:

$$p = p_{ab} + p_{bc} = u_{RS}i_R - u_{ST}i_T = u_R i_R - u_S(i_R + i_T) + u_T i_T$$

and since $i_R + i_S + i_T = 0$, results:

$$p = u_R i_R + u_S i_S + u_T i_T$$

The PV expressions (13) and (14) demonstrate that the channel *ab* transmits the instantaneous power:

$$p_{ab} = u_{RS}i_R = \sqrt{3}\hat{U}\,sin(\omega t + \pi/6)\left[-\hat{I}\,cos(\omega t)\right] = = -\sqrt{3}UI\left[\frac{1}{2} + sin(2\omega t + \pi/6)\right] \qquad (15)$$

and the channel *bc* transmits the power:

$$p_{bc} = -u_{ST}i_T = -\sqrt{3}\hat{U}\,sin(\omega t - \pi/2)\left[-\hat{I}\,cos(\omega t + 2\pi/3)\right] = = \sqrt{3}UI\left[\frac{1}{2} + sin(2\omega t + \pi/6)\right] \qquad (16)$$

At every moment the net power transferred to the load via the channels *ab* and *bc* is zero, nevertheless, equations (15) and (16) clearly show that energy oscillations between the source and the load do take place and are not *"illusions"* as claimed in [11]. These power oscillations are represented in Figure 2 by mean of PV. For the sake of simplicity the three-phase line was assumed lossless. If a lossy line is considered, every PV stream line has a small radial component [8, 9] that supplies the conductor with energy that is converted in Joule and eddy current losses. The conclusion derived from (15) and (16) about oscillations holds true for any line and conductors geometry and for any three-phase conditions.

If the inductive load is replaced with a purely resistive load then the power carried by PV through the channel *ab* is:

$$p_{ab} = u_{RS} i_R = \sqrt{3}\hat{U}\, sin(\omega t + \pi/6)\hat{I}\, sin(\omega t) = \\ = \frac{3}{2}UI - \sqrt{3}UI\, cos(2\omega t + \pi/6) \qquad (17)$$

and through the channel *bc*:

$$p_{bc} = -u_{ST} i_T = -\sqrt{3}\hat{U}\, sin(\omega t - \pi/2)\hat{I}\, sin(\omega t + 2\pi/3) = \\ = \frac{3}{2}UI + \sqrt{3}UI\, cos(2\omega t + \pi/6) \qquad (18)$$

The total power is now constant, $p = p_{ab} + p_{bc} = 3UI$, nevertheless expressions (17) and (18) reveal the existence of intrinsic powers that are power oscillations associated with the transmission of active power.

3. THE CONTROVERSIAL PRESENCE OF $\vec{\wp} = \vec{E} \times \vec{H}$ WHEN NO ENERGY FLOW TAKES PLACE

Reference [13] argues that *"a common electrical engineer may need the expertise of an expert in electromagnetic fields to have an opinion on this matter."* To support such a claim Prof. Czarnecki [13, 14] brings from the past an old puzzle, the MacDonald's paradox [18], a condition which was explained in the 1960s by top scientists like R. P. Feynman [15] and W. Shockley [16, 17] using the concept of momentum of electromagnetic field. The system in question is sketched in Figures 3a and b where a permanent magnet or a winding carrying a direct current is immersed in a time-invariant uniform electric field. In such condition, though the fields are static, there is a dynamic flux of energy characterized by a PV with a distinct distribution in the observed space.

To the "expert of experts" eye the PV in such case is an obvious solenoidal vector, the Heaviside vector $\vec{G}$ from (2), and such vector yields a zero-flux through any closed volume.

For the "common" electrical engineer with knowledge limited to basic field theory the truth may become apparent by replacing the magnet with two parallel conductors, Figure 3c. The solution is found by using the superposition of the contributions made by each conductor. In Figure 4 is sketched one conductor carrying the current *i* and immersed in a

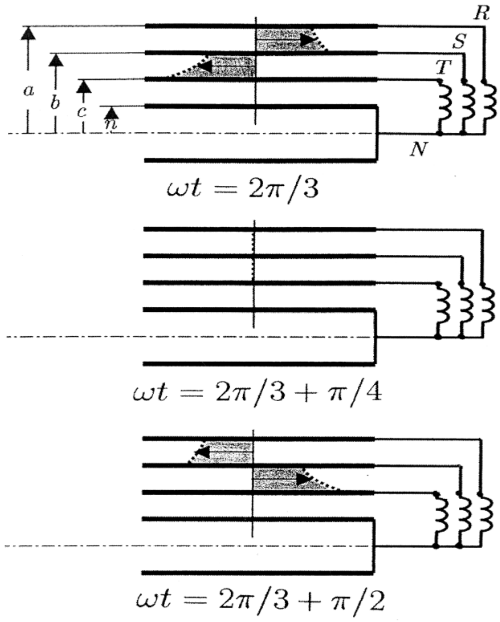

Fig. 2. Power Oscillations are not Illusions: Poynting Vector Distribution at Three Different Moments, Inside a Coaxial Three-Phase Line Supplying a Zero Power Factor Balanced Load

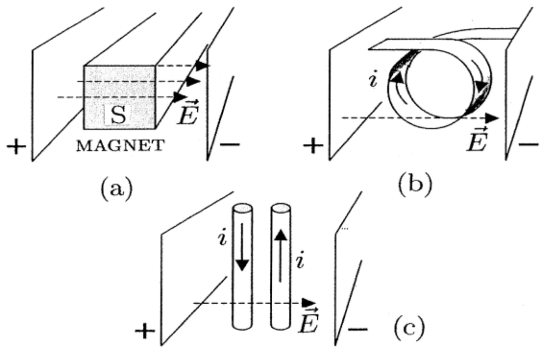

Fig. 3. Situations where a Solenoidal PV is Produced and no Energy is Transferred: Uniform Electric Field and Permanent Magnet; (b) A Current Carrying Loop Immersed in Uniform magnetic Field; (c) Two Parallel Conductors Carrying Opposing and Equal Currents

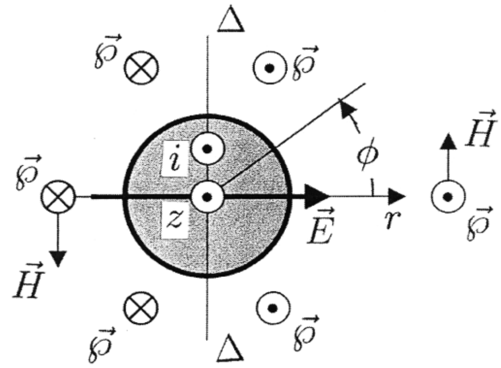

Fig. 4. The PV Around a Conductor Immersed in a Uniform Electric Field

uniform field E. Just by visual inspection of Figure 4 one observes that the vertical plane $\Delta-\Delta$ separates the space in two regions where on the right side the PV flux enters the paper and on the left side exits. Since the system is symmetric the flux in equals the flux out and the net PV flux is nil. If one is comfortable with elementary calculus the following path leads to a straight answer: The magnetic field inside and outside the conductor are:

$$\vec{H} = \frac{i}{2\pi a^2} r \vec{1}_\phi \quad \text{for} \quad 0 \le r \le a \tag{19}$$

$$\vec{H} = \frac{i}{2\pi r} \vec{1}_\phi \quad \text{for} \quad r \ge a \tag{20}$$

The respective PVs can be readily found:

$$\vec{\wp}' = \vec{E} \times \vec{H} = \frac{Ei}{2\pi a^2} r \cos\phi \vec{1}_z \quad \text{for} \quad 0 \le r \le a \tag{21}$$

$$\vec{\wp}'' = \vec{E} \times \vec{H} = \frac{Ei}{2\pi r} \cos\phi \vec{1}_z \quad \text{for} \quad r \ge a \tag{22}$$

and the total PV flux that flows, in z-direction, through a large cylinder with radius $r = \Re$, concentric with the conductor is $p = p' + p'' = 0$, where:

$$p' = \int_{r=0}^{a} \int_{\phi=0}^{2\pi} \vec{\wp}' \cdot (\vec{1}_z) r dr d\phi = \frac{Ei}{2\pi a^2} \int_{r=0}^{a} \int_{\phi=0}^{2\pi} r^2 \cos\phi dr d\phi = 0$$

and:

$$p'' = \int_{r=0}^{\Re} \int_{\phi=0}^{2\pi} \vec{\wp}'' \cdot (\vec{1}_z) r dr d\phi = \frac{Ei}{2\pi} \int_{r=a}^{\Re} \int_{\phi=0}^{2\pi} \cos\phi dr d\phi = 0$$

4. THE UNBALANCED LOAD CASE

The same three-phase concentric geometry is assumed to supply the extreme case of unbalance where a resistive load R is connected line-to neutral, Figure 5. In this case the currents are:

$$i_R = -i_N = \frac{\hat{U}}{R} \sin(\omega t) \quad \text{and} \quad i_S = i_T = 0$$

In spite of the fact that $i_s = i_t = 0$, the magnetic field is present in all three channels, ab, bc and cn. Moreover, the instantaneous powers supplied by the sources u_S and u_T are nil, but the interaction of the electric and magnetic fields in channel bc produces a PV that carries instantaneous powers. Expressions (8) to (14) lead to the following instantaneous powers impinged through the channels:

$$p_{ab} = \frac{3}{2}\frac{U^2}{R} - \sqrt{3}\frac{U^2}{R} \cos(2\omega t - \pi/6) \tag{23}$$

$$p_{bc} = -\sqrt{3}\frac{U^2}{R} \cos(2\omega t - \pi/2) \tag{24}$$

$$p_{cn} = -\frac{U^2}{2R} - \frac{U^2}{R} \cos(2\omega t + 2\pi/3) \tag{25}$$

A most interesting picture unfolds when the first two terms are rearranged by separating the load power from its intrinsic powers:

$$p_{ab} = \frac{U^2}{R} - \frac{U^2}{R}\cos(2\omega t) + \frac{U^2}{2R} + \frac{U^2}{R}\cos(2\omega t - 2\pi/3)$$

and:

$$p_{bc} = -\frac{U^2}{R}\cos(2\omega t - 2\pi/3) + \frac{U^2}{R}\cos(2\omega t + 2\pi/3)$$

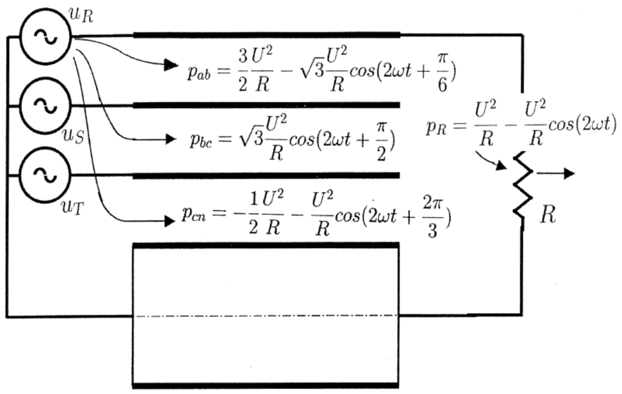

Fig. 5. Three-Phase Positive-Sequence Voltage Supplying One Resistance Connected Line-to-Neutral via a Coaxial Three-Phase Cable. Instantaneous Powers Flow and its Expressions

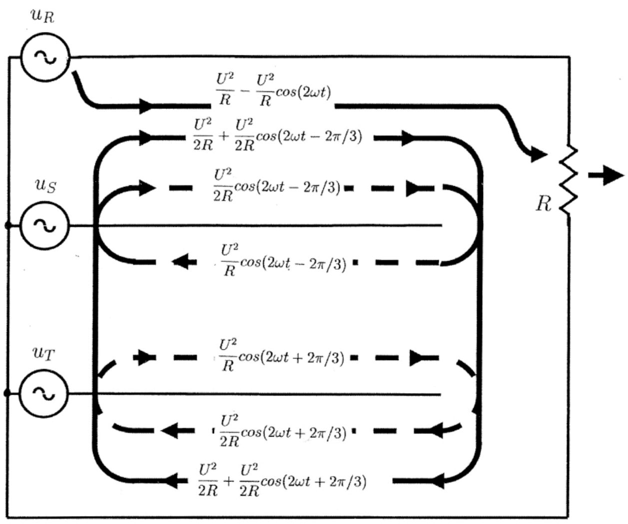

Fig. 6. Separation of Instantaneous Powers in Figure 5 when the Intrinsic Powers are Accounted

The flow of power is depicted in Figure 6. It is quite surprising to realize that the flux of electromagnetic powers involves loops with no net energy transfer. Is such an observation going to *“solve something previously unsolved?....Do they provide data for tariffs?”* [13], the answer at this moment is no! *“Do powers interpreted and specified in terms of Poynting vector ...deepen physical interpretation[s]?”* [13]. Based on this section’s result some folks of vision may answer yes!

5. SINGLE-PHASE: THE GENERAL CASE

A single-phase circuit supplying a nonlinear load with a current i from a sinusoidal voltage u_S through a line with resistance R_S and inductance L_S, Figure 7a, can be analyzed using Figure 7b, where the nonlinear load is represented by means of the equivalent fundamental voltage u_1 and the total harmonic voltage u_H. In turn, the current is separated in two similar components, i_1 and i_H. The fundamental current i_1 can be further separated in a component i_{p1} in-phase with u_1 and a component i_{q1} in-quadrature with u_1. From Kirchhoff’s voltage law results:

$$u_S = R_S i_1 + L_S \frac{di_1}{dt} + u_1 \qquad (26)$$

$$u_H = R_S i_H + L_S \frac{di_H}{dt} \qquad (27)$$

The interaction between the electric fields produced by the voltages u_S and u_H, and the magnetic fields due to the currents i_{p1}, i_{q1} and i_H, yields the following five elementary powers:

$$u_S i_{p1} = R_S i_1 i_{p1} + L_S i_{p1} \frac{di_1}{dt} + u_1 i_{p1} \qquad (28)$$

$$u_S i_{q1} = R_S i_1 i_{q1} + L_S i_{q1} \frac{di_1}{dt} + u_1 i_{q1} \qquad (29)$$

$$u_S i_H = R_S i_1 i_H + L_S i_H \frac{di_1}{dt} + u_1 i_H \qquad (30)$$

$$u_H i_1 = R_S i_1 i_H + L_S i_1 \frac{di_H}{dt} \qquad (31)$$

$$u_H i_H = R_S i_H^2 + L_S i_H \frac{di_H}{dt} \qquad (32)$$

These equations provide the information for the complete representation of the instantaneous power flow summarized in Figure 8. Evidently, the use of basic circuit theory will be sufficient to obtain each one of these equations. Nevertheless, we shall keep in mind that each one of these

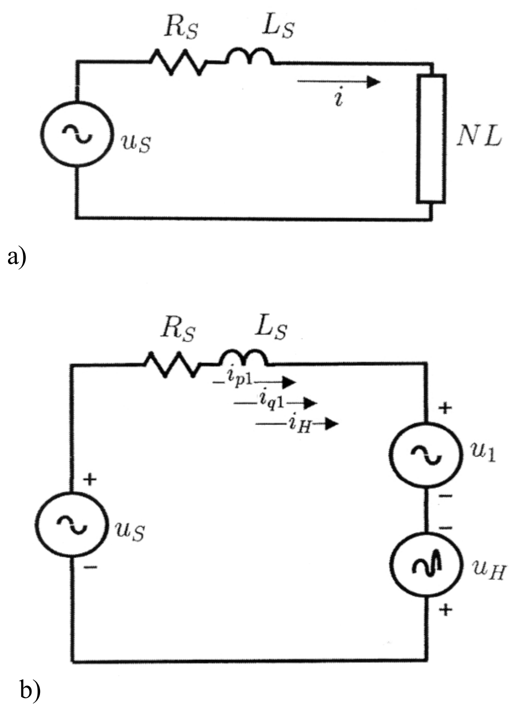

Fig. 7. Nonlinear Load in a Single-Phase Basic Circuit: (a) Circuit; (b) The Nonlinear Load is Replaced by Equivalent Fundamental and Harmonic Voltages

five powers is backed-up by PV components whose electromagnetic wave travels through the dielectric surrounding the conductors. Equations (28) to (32) alone do not disclose the distribution of powers in space. We saw in the previous three-phase examples that basic circuit theory is not sufficient to describe the power distribution in space. The vast majority of engineers believe that power flow is constrained to conductors’ volume. Only the engineers involved in higher frequency applications, aware of the penetration depth, that is limited be eddy currents, are familiar with the PV. A meter, or an energy quality monitoring instrument, connected at the load terminals can measure or detect the five different powers. Assuming for the expression of load voltage and currents:

$$u = \hat{U}_1 \sin(\omega t) + \sum_{h \neq 1} \hat{U}_h \sin(h\omega t + \alpha_h) \qquad (33)$$

$$i = \hat{I}_1 \sin(\omega t - \vartheta_1) + \sum_{h \neq 1} \hat{I}_h \sin(h\omega t + \alpha_h - \vartheta_h) \qquad (34)$$

results that the five instantaneous powers are:

$$p_{p1} = u_1 i_{p1} = U_1 I_1 \cos(\vartheta_1)[1 - \cos(2\omega t)]$$

$$p_{q1} = u_1 i_{q1} = -U_1 I_1 \sin(\vartheta_1) \sin(2\omega t)$$

$$p_{DI} = u_1 i_H = 2U_1 \sum_{h \neq 1} I_h \sin(\omega t) \sin(h\omega t + \alpha_h - \vartheta_h) =$$

$$= \sum_{h \neq 1} D_{Ih} \left[\cos[(h-1)\omega t + \alpha_h - \vartheta_h] - \cos[(h+1)\omega t + \alpha_h - \vartheta_h] \right]$$

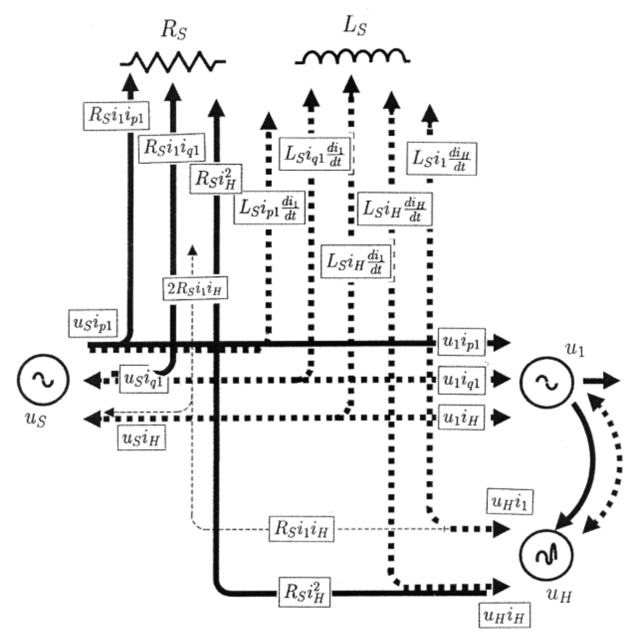

Fig. 8. The Instantaneous Power Flow of Figure 7

$$p_{DV} = u_H i_1 = 2I_1 \sum_{h \neq 1} V_h \sin(\omega t - \vartheta_1) \sin(h\omega t + \alpha_h) =$$

$$= \sum_{h \neq 1} D_{Vh} \left[\cos[(h-1)\omega t + \alpha_h + \vartheta_1] - \cos[(h+1)\omega t + \alpha_h - \vartheta_1] \right]$$

$$p_H = u_H i_H = \sum_{h \neq 1} P_h [1 - \cos(2h\omega t + 2\alpha_h)] -$$

$$-\sum_{h \neq 1} Q_h \sin(2h\omega t + 2\alpha_h) + \sum_{h \neq 1} U_m I_n \begin{bmatrix} \cos[(m-n)\omega t + \alpha_m - \alpha_n + \vartheta_n] \\ -\cos[(m+n)\omega t + \alpha_m + \alpha_n - \vartheta_n] \end{bmatrix}$$

The instantaneous power dissipated in R_S is:

$$\Delta p = R_S (i_1 + i_H)^2$$

yielding an average power:

$$\Delta P = R_S (I_{p1}^2 + I_{q1}^2 + I_H^2); \qquad I_H^2 = \sum_{h \neq 1} I_h^2$$

To determine the correlation between the apparent power $S = UI$ and the power lost in line one computes $\Delta P = R_S S^2 / U^2$, where $U^2 = U_1^2 + U_H^2$. The result is:

$$\Delta P = \frac{R_S}{U^2} \left[(U_1 I_{p1})^2 + (U_1 I_{p1})^2 + (U_1 I_H)^2 + (U_H I_1)^2 + (U_H I_H)^2 \right] \quad (28)$$

where:

$U_1 I_{p1} = P_1$ is the fundamental apparent power,

$U_1 I_{q1} = Q_1$ is the fundamental reactive power,

$(U_1 I_H)^2 = \sum_{h \neq 1} (U_1 I_h)^2 = \sum_{h \neq 1} D_{Ih}^2$ is the current distortion power squared,

$(U_H I_1)^2 = \sum_{h \neq 1} (U_h I_1)^2 = \sum_{h \neq 1} D_{Vh}^2$ is the voltage distortion power squared

$(U_H I_H)^2 = \sum_{h \neq 1} (U_h I_h)^2 + \sum_{\substack{m \neq n \\ m,n \neq 1}} (U_m I_n)^2 = \sum_{h \neq 1} P_h^2 + \sum_{h \neq 1} Q_h^2 + \sum_{h \neq 1} D_{mn}^2$ is the harmonic apparent power.

To each one of these elementary power components corresponds a distinct PV component.

6. IS THERE SOMETHING WRONG WITH THE POYNTING VECTOR?

Stanislaw Fryze's interpretation of power was based on separation of current in two components, an active current with a waveform that is an exact replica of the voltage waveform (31), i.e.:

$$i_a = G \sum_{h=1} \hat{U}_h \sin(h\omega t + \alpha_h)$$

where the conductance G satisfies the condition:

$$P = \sum_{h=1} U_h I_h \cos(\vartheta_h) = G \sum_h U_h^2$$

and a nonactive current $i - i_a$.

The components of the active current i_a are supporting the active powers $P_{ah} = GU_h$. Since $GU_h^2 \neq U_h I_h \cos(\vartheta_h)$ the PV active components do not correspond with P_{ah} at all, they correlate only with $P_h = U_h I_h \cos(\vartheta_h)$.

The significance of this observation gains importance when one thinks about the power flow to a synchronous or to an asynchronous machine. The useful power that produces the dominant torque is carried by the fundamental positive sequence component of the PV, $P_1 = U_1 I_1 \cos(\vartheta_1)$ and not by GU_1. In typical modern power networks induction motors make for more than 60% of the loads. The power model proposed by Fryze and favored by Prof. Czarnecki does not seem to provide immediate information on this dominant power component. Could this be the root for the PV rejection?

7. CONCLUSIONS

The so called power theory is not limited to the "*question of why the apparent power at the junction of a load and energy supplier could be higher than the active power; how to derive and interpret various non-active powers and how to compare them.*" [13 discussion]. A good engineer and scientist will try to understand the physical mechanism that controls the flow and conversion of energy and will hike all the way to the peak of the mountain where a clear vista of the time variations and spatial distribution of the fields and electromagnetic powers are obtained.

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