Comments on "Physical Interpretation of the Reactive Power in Terms of CPC Power Theory Revisited"

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Summary: The paper evaluates the possibility of formulating the Currents' Physical Component (CPC) – based power theory in the time-domain. It was concluded that the currents' physical components, defined originally in the frequency-domain, can be calculated in the time-domain, but there is still the lack of their physical interpretation in that domain.

***Key words**: power definitions, scattered power, scattered current, harmonic generating loads, HGL, harmonic generated power, finite energy signals*

1. INTRODUCTION

As the author of the CPC-based power theory I would like to recognize Drs. Jeltsema's and van der Woude's attempts aimed at formulating that theory in the time-domain, as presented in Ref. [1].

The CPC-based power theory was originally formulated in the frequency-domain, meaning with the use of a concept of harmonics and admittances for harmonic frequencies. Equivalent formulation of that theory in the time-domain would positively contribute to strengthening its fundamentals.

Power theory of electrical systems is developed mainly for cognitive reasons: we would like to understand physical phenomena that accompany energy transfer. It is also developed for practical reasons: we would like to know how undesirable phenomena that accompany energy flow could be suppressed. The adjective "physical" in the name "Currents' Physical Component", (CPC), has therefore, a crucial importance. It means that each current component in the CPC-based power theory can be associated with a distinctive physical phenomenon in the circuit that can be observed by measurement.

In this paper we will investigate if the current decomposition presented in Ref. [1] can be regarded as decomposition into currents' physical components in the time-domain and its cognitive merits.

2. ENERGY RELATED PHYSICAL PHENOMENA N SINGLE-PHASE LOADS

Let us review the energy flow related physical phenomena in single-phase loads, which are associated according to CPC-based power theory with currents' physical components.

The concept of the reactive current $i_r(t)$, as used in the CPC-based power theory, was introduced by Shepherd and Zakikhani in Ref. [2]. Complex notation is only CPC–based modification.

If a periodic supply voltage of ω_1 frequency is expressed in terms of the Fourier series

$$u = U_0 + \sqrt{2}\sum_{n=1}^{\infty} U_n \cos(n\omega_1 t + \alpha_n) = = U_0 + \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty} \boldsymbol{U}_n\, e^{jn\omega_1 t} \tag{1}$$

then the load current

$$i = I_0 + \sqrt{2}\sum_{n=1}^{\infty} I_n \cos(n\omega_1 t + \alpha_n - \varphi_n) = = I_0 + \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty} \boldsymbol{I}_n\, e^{jn\omega_1 t} \tag{2}$$

can be decomposed into following components:

$$i_\mathrm{R} = I_0 + \sqrt{2}\sum_{n=1}^{\infty} I_n \cos\varphi_n \cos(n\omega_1 t + \alpha_n) = = I_0 + \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty} G_n\, \boldsymbol{U}_n\, e^{jn\omega_1 t} \tag{3}$$

$$i_\mathrm{r} = \sqrt{2}\sum_{n=1}^{\infty} I_n \sin\varphi_n \sin(n\omega_1 t + \alpha_n) = = \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty} jB_n\, \boldsymbol{U}_n\, e^{jn\omega_1 t} \tag{4}$$

where G_n and B_n denote the load conductance and susceptance for frequency $n\omega_1$.

The component i_r was called a "reactive current" in Ref. [2]. It is a current component, which is equal to the sum of components of the current harmonics shifted by $\pi/2$ with respect to the supply voltage harmonics. The phase-shift is observable in an experiment shown in Fig. 1, with a generator which supplies the load with a sinusoidal voltage of the $n\omega_1$

frequency. The load susceptance B_n can be calculated from meters' readings.

Now, let us see how the reactive current occurs in decomposition developed in Ref. [1] in Section 4.

The admittance of LTI loads $Y(j\omega)$ is a Hermitian function, meaning

$$Y(-j\omega) = Y^*(j\omega) \tag{5}$$

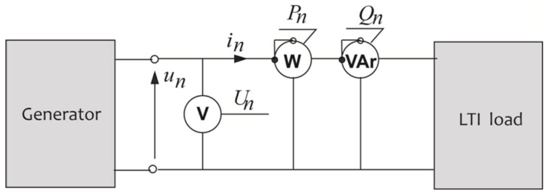

Fig. 1. Test circuit for measurement of the admittance for the nth order harmonic

and consequently, its imaginary part, $B(j\omega)$, is an odd function of frequency. Its Inverse Fourier Transform, a function of time, denoted in Ref. [1] as $h_o(t)$, is consequently an odd function of time as well. Its convolution with the supply voltage $u(t)$, denoted in Ref. [1] by symbol $y_\perp^*(t)$, is claimed to be the reactive current. Unfortunately, even if this is true, it was not proven in Ref. [1] that indeed

$$y_\perp^*(t) \equiv i_r(t) \tag{6}$$

Such a proof is needed especially because the illustration of the Kramers-Kronig relationship in Fig. 3 is erroneous. Function $H(\omega)$ in this figure is not a Hermitian function. To be Hermitian, real part should be an even function and imaginary an odd.

Assuming that indeed current $y_\perp^*(t)$ is the reactive current, then how is this current associated with a physical phenomenon in the load, without going outside of the time-domain concept, meaning not using terms from the frequency-domain, such as "the phase-shift", "harmonics", and "susceptance"?

All that was told above about the reactive current applies also to the scattered current. It was introduced in the CPC-based power theory because in the case of loads with not constant conductance G_n, the resistive current $i_R(t)$ in the Shepherd's decomposition is higher (in terms of rms value) than the active current, i.e., the supply current of a purely resistive load of conductance G_e, which is equivalent to the original load with respect to the active power P. The difference of these two currents is the scattered current:

$$i_s = (G_0 - G_e)U_0 + \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty}(G_n - G_e)\boldsymbol{U}_n\, e^{jn\omega_1 t} \tag{7}$$

Thus, it occurs in the load current because of the change of the load conductance G_n with the harmonic order. What physical phenomenon observable in time-domain is responsible for the scattered current existence?

If the authors claim that they developed the Currents' Physical Components – based power theory in the time-domain, the current physical components should be associated with physical phenomena observable in just this domain. Otherwise, we can conclude only, that particular physical components can be calculated in the time-domain, but their physical interpretation still requires concepts and terminology taken from the frequency-domain. It seems that just the awareness of existence of phenomena of the phase-shift and change of conductance with harmonic order, which are observable in the frequency-domain, has provided a major incentive for a quest of the equivalent of CPC in the time-domain.

Such a physical interpretation would really contribute to the power theory development. Therefore, we can encourage authors of Ref. [1] for continuation of investigation in this direction.

The results of Section 4 are promising, but some conditions require clarification. More mathematical precision is needed to make the concept presented in Section 4 of Ref. [1] clear. First, over what interval of time does the input voltage $u(t)$ have to be integrable: over a period T or over infinity? How are the scalar product and rms value defined? The period of quantities involved in the energy transfer does not occur in Section 4; thus, are the results obtained valid for non-periodic quantities? Are these quantities of finite energy or finite power? If the decomposition, as presented in Section 4, is valid for quantities of finite energy, then this decomposition would be a time-domain equivalent of the CPC-based power theory of LTI systems with non-periodic quantities, developed in the frequency-domain, as presented in Ref. [3].

3. POWER PHENOMENA IN CIRCUIT WITH TRIAC

The current decomposition as developed for linear systems in Section 4, when applied to a load with a TRIAC has provided results that have nothing in common with the CPC-based power theory. The currents defined in Section 4, although called the reactive and scattered currents, are not the reactive and scattered currents as defined in the CPC. They are not associated with physical phenomena responsible for the presence the reactive and the scattered currents.

The authors of Ref. [1] analyzed, in the time-domain, power properties of a load, shown in Fig. 2, discussed earlier in Ref. [4].

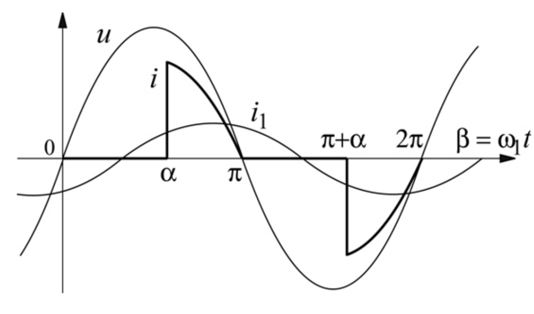

Fig. 3. The supply voltage and the load current waveforms

Meter readings, shown in Fig. 2, were calculated at the assumption that the voltage rms value was $U = 220$V and the TRIAC's firing angle α =135 deg.

The supply current is distorted because of two mechanisms. The first of them is switching ON at firing angle α of the TRIAC, thus time-variance of the load resistance. The second is switching OFF the current because of the TRIAC's non-linearity when its current reaches zero value. These two mechanisms, along with the supply voltage and the resistance values, shape the load current $i(t)$ waveform, as shown in Fig. 3.

There is no phenomenon in the circuit other than time-variance of the load resistance and its nonlinearity, along with the circuit parameters in the ON state that would be responsible for the current waveform. For the circuit under consideration, mechanisms which shape the current waveform (time instances of switching ON and OFF) are specified entirely in the time-domain.

The load current can be expressed as a sum of harmonics. Since the supply voltage is assumed to be sinusoidal, there is no other component of the reactive current than that associated with the phase-shift between the voltage and the fundamental component of the load current $i_1(t)$.

Since the supply voltage is sinusoidal, then only one harmonic of the voltage and current, the fundamental one, is responsible for permanent delivery of energy to the load and its active power P. Thus, the phenomenon associated with increase of the supply current because change of the load conductance G_n with harmonic order does not exist. Consequently, there is no scattered component in the supply current as well. Current harmonics other than the fundamental one, which occur as a combined effect of load parameters time-variance and non-linearity, contribute only to the load current rms value increase. They form a current referred to in the CPC as a ***generated current***. Unfortunately, phenomenon of such a current harmonic generation is not revealed in Ref. [1].

4. CONCLUSIONS

The current decomposition as presented in the Ref. [1] cannot be regarded as the time-domain equivalent of the CPC, formulated originally in the frequency-domain. Maybe, it might enable only that the current components, as defined in the CPC – based power theory, be calculated in the time-domain. To be regarded as the time-domain equivalent of the CPC, it should provide time-domain based physical interpretation of energy related phenomena, without frequency-domain approach and terms. Results of the presented approach as applied in Ref. [1] to a circuit with TRIAC cannot be regarded as the CPC-based description of power phenomena in such a circuit.

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