CPC AND IEEE POWER THEORY – APPLICATION FOR OFFLINE WAVEFORM DATA ANALYSIS

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ABSTRACT

In our work we have focused on studying various definitions of electric power in complex situations. We have created a set of analytical tools to calculate power components according to the IEEE 1459-2010 standard and the Current's Physical Components theory. We use these tools for offline analysis of real measured data. Used data include steady states as well as transients of several common appliances, and also some power quality related phenomena is covered.

INTRODUCTION

During the existence of power grids there have been efforts to reach maximum efficiency of power transfer from the supplier to the end user. Power can be transmitted both through DC and AC. The DC grids are not an issue for power quality yet. Main subject of our interest are AC grids.

Optimization of such systems requires a good description of the ongoing physical phenomena. However, there is so far not any unified theory to give good information on what is going on in the most complex circuits under the conditions of distorted and asymmetrical voltage and current. There are many theories describing the flow of energy. Each of them has slightly different approach and thus gives different kind of information.

Basic recommendation on how to calculate power components in various situations is given in an IEEE standard [1]. Quite different approach is given in the CPC theory [2]. This article tries to point out some aspects in which these theories differ from each other, and also some things that are common to both. Both methods were implemented and offline tested on real measured data. Outputs of our analysis are graphical figures, depicting flow of power components in time to a specific appliance.

BASIC FORMULAE

Power quantities are always defined as an aggregated value per a time interval, except for instantaneous power [1] which is of relatively low practical importance. Such aggregation interval should be a multiple of fundamental period (i.e. $T = 0.02\ s$ in systems with fundamental frequency $f = 50\ Hz$).

1. IEEE 1459-2010 Definitions

Definitions given in this standard are rather straightforward. Various scenarios are covered, such as single-phase sinusoidal or distorted voltage (current), or three-phase sinusoidal, distorted or unbalanced voltage (current). Of our interest is single-phase system with harmonic distortion. We use these definitions to analyse systems both in steady state and during slow state transition (longer than a multiple of fundamental period).

IEEE definitions utilize the Fourier transform and in three-phase systems also the Fortescue phasor decomposition [7]. Basic idea is to split general apparent power

$$S = \|u(t)\|\,\|i(t)\| \quad (1)$$

into active and nonactive components:

$$P = \frac{1}{T}\int_0^T u(t)i(t)dt, \quad N = \sqrt{S^2 - P^2} \quad (2)$$

Further, fundamental and harmonic components are defined. These are useful for describing harmonic distortion in the system.

$$P_1 = U_1 I_1 cos\varphi_1, \quad Q_1 = U_1 I_1 sin\varphi_1 \quad (3)$$
$$S_1 = U_1 I_1, \quad S_H = U_H I_H \quad (4)$$
$$D_I = U_1 I_H, \quad D_V = U_H I_1 \quad (5)$$

Reader should be aware of possible confusion of nonactive power and reactive power. Nonactive power N contains all non-utilizable and undesired power. Reactive power is present when voltage and current phasors of certain harmonic are not parallel, but have a phase shift. In the IEEE standard [1], single-phase reactive power Q_1 is defined for fundamental frequency only. For further insight into terminology refer to [3].

In three-phase scenarios all the above mentioned definitions have, using the Fortescue decomposition, the positive-, negative- and zero-sequence power components.

2. The Current's Physical Components Concept

The CPC theory introduces a different approach to power components definitions. Following S. Fryze's theory [6] and utilizing the Fourier transform it decomposes the measured current into several mutually orthogonal components. Each current component appears only when certain kind of distortion is present - thus we get active current, reactive current (present when voltage and current are phase-shifted to each other), scattered current (present, when character of the load changes with frequency), generated current (active power is delivered from the load to the grid) and, in three-phase systems, unbalanced current.

Power definitions are derived from RMS value of each of these currents and the overall voltage RMS. It can be shown that geometrical sum of these power components gives the same apparent power as in [1]. Also, the active power equals to the one defined in [1], if non-negative. (For further details on these definitions please refer to [2].)

$$i_a(t) = \sqrt{2}\sum_{n\in D} Re\{G_{en}\hat{U}_n e^{j\omega t}\},\quad P = \|i_a\|\|u\| \quad (6)$$

$$i_r(t) = \sqrt{2}\sum_{n\in D} Re\{jB_n\hat{U}_n e^{j\omega t}\},\quad Q = \|i_r\|\|u\| \quad (7)$$

$$i_s(t) = \sqrt{2}\sum_{n\in D} Re\{(G_n - G_e)\hat{U}_n e^{j\omega t}\},$$

$$D_s = \|i_s\|\|u\| \quad (8)$$

$$i_C(t) = \sqrt{2}\sum_{n\in C} Re\{\hat{I}_n e^{j\omega t}\},\quad S_C = \|i_C\|\|u\| \quad (9)$$

The CPC theory requires knowledge of the measured load. If unknown (as is our case), the load's complex admittance $Y = G + jB$ needs to be calculated from sampled voltage and current. However, this is impossible for three-phase delta-configuration systems.

By defining the power components non-negative, the CPC deals with a problem found in the Budeanu theory [5]. For the original Budeanu's definitions it was proved that even with non-zero reactive powers of the harmonics, the sum of these can be zero, and thus the computations might show the power factor close to one. In the CPC the reactive powers of harmonics are summed geometrically ([2], form. 7), and thus the problem is avoided. In the IEEE there is no such corresponding reactive power component defined at all.

IMPLEMENTATION AND ANALYSIS

For the purpose of analysis we have developed a set of tools, enabling easy calculation of the above mentioned definitions. The input data are mostly sampled at $F_s = 6{,}400$ *Hz*, i.e. 128 samples per period by using class S power quality analyzers SMPQ and BRAVO [8].

The input data are windowed to a single fundamental period. After calculating all desired power components from this period, the results are stored, the window is shifted forward by one sample, and the calculations are performed again. This sliding-window principle allows creation of output data series appearing as a function of time. However, to interpret and treat them as a function of time would be wrong. The resulting data are stored in a file in CSV format for later utilization, such as creation of graphical figures.

As both of the theories utilize the Fourier transform, periodicity of the input signal is supposed. Neither of them is therefore suitable for analyzing transients faster than the length of the used sliding window (i.e. one period). In such case the results would be purely mathematical constructions with no real basis.

As the area of interest in this article are single-phase systems, the analyzed datasets cover consumption of common office appliances, such as personal computers, discharge lamps, a ventilator, etc. The sampled time series are always long enough to contain the transients caused by turning the appliance on / off, as well as the steady states.

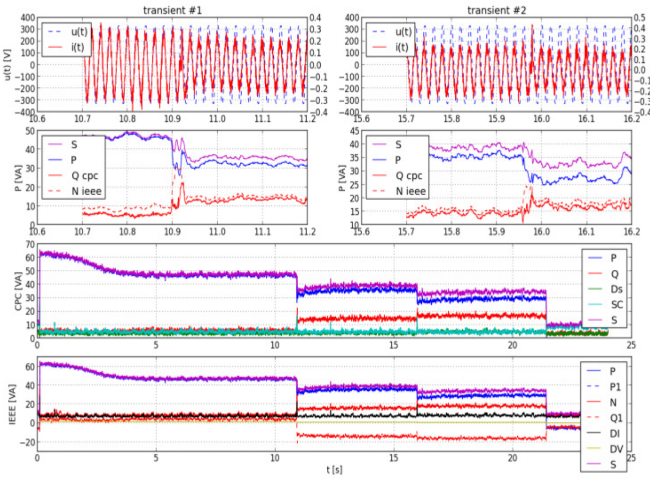

Fig. 1: An office fan during various changes in its operations – waveform of selected state transformation on top, with S, P, Q and N comparison during the same interval below; overview of the whole measurement (bottom).

Figure 1 depicts results of the analysis of an office fan. One can observe that the reactive power is gaining when operating on lesser speeds. On the startup the power consumption is slightly higher due to the acceleration of the fan. From the same reason the power consumption drops slightly as the fan decelerates to smaller speeds.

Apart from some properties of the appliance, one can also conclude on certain aspects of the theories. Firstly, it is obvious that in the CPC theory none of the power components can get negative. Therefore one cannot differentiate between capacitive and inductive load. The IEEE definitions suggest that the load is capacitive (fundamental reactive power gets negative). From the proximity of active and apparent powers in both theories it can be seen that the power factor is close to one when running on the highest speed (the fan is apparently compensated to run on this level) and gets slightly worse on other levels. In the IEEE definitions one can see that the voltage is not distorted at all (the D_V power component sticks to zero), while, looking at the D_I component, the current is slightly distorted. However, any additional power transferred by this harmonic distortion is insignificant, as the distortion is on the current quantity only. This also results in good proximity of the fundamental apparent power S_1 to general apparent power S. Such kind of distortion is reflected in the CPC theory as the scattered power D_s and generated power S_C, which also rises when the active power P gets negative.

On the figure 2 there is shown an analysis of turning a PC display on and off. It can be seen that the power factor is far from ideal value not only during the warm-up phase (time *1.2 - 4 s*) but also in the mode of normal operation (time *4 - 8 s*), and that certain level of distortion is injected into the grid even in the stand-by mode (time *0 - 1 s*). From the IEEE definitions we can see that the appliance generally has a capacitive character (negative Q_1).

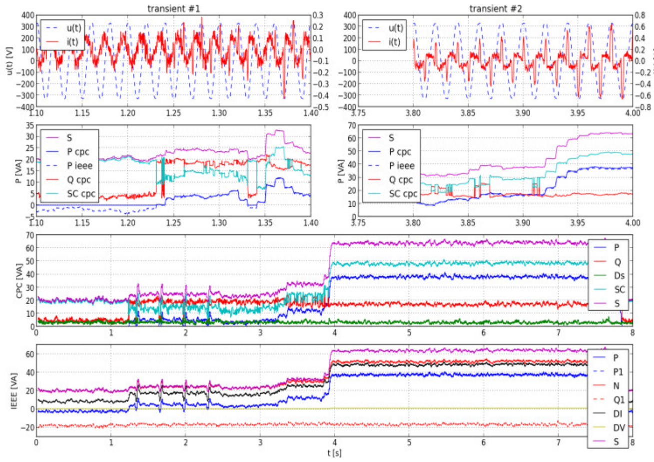

Fig. 2: Power consumption during boot-up of a PC display

In the standby mode the active power is zero or slightly negative, which means that almost all consumed apparent power is transformed into reactive power and / or distortion. In such case the CPC shows high generated power component, which is almost equal to apparent power.

The reason why figure 3 (a PQ related event, data acquired from [9]) is presented is to show an aspect typical for the CPC analysis. Sometimes there are visible certain fluctuations of power between the generated power and the rest of the components. This is observed when active power of one or more harmonics is close to zero. However small the active power is, when positive, the given harmonic contributes to other components (here Q). When the active power gets negative, the entire harmonic contributes to generated power component only.

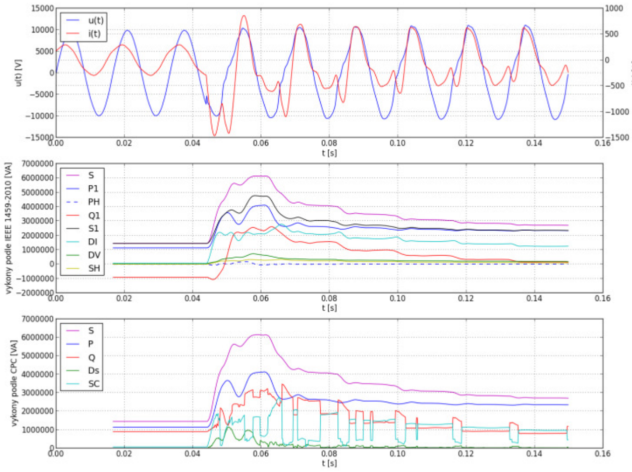

Fig. 3: A power quality disturbance [9]

If such fluctuations occur periodically, it can be assumed that it is merely a result of interpretation of the FFT, calculated on the windowed fundamental period, with the phase of certain harmonic being very close to p/2 rad, or 3p /2 rad.

CONCLUSION

In our work we have developed an implementation of two distinct electric power calculations. The calculations were run on real measured data. From the resulting figures it can be seen the way the given appliance behaves in different modes of operation, as well as during transients. Used methods allow analysis of transients longer than a few fundamental periods. Apart from the analysis itself, certain aspects of the two implemented approaches can be discussed.

The definitions of the CPC theory state that all power components are non-negative. This means that for example the reactive power has same value for capacitive and inductive load. However, when the appliance behaves as a source of power (i.e. the active power of certain harmonic would get negative), the given harmonic is categorized to the generated power component (even the fundamental frequency, which differs from the others only by its order of magnitude). Thus the generated power component describes the backwards "generation" of the power (generally distortion). In an extreme case where the generated power is equal to the apparent power (see fig. 2) it might be viewed that the appliance consumes apparent power and sends it all back to the grid in the form of distortion.

However, when the given harmonic is transferred into generated power component, we lose the information on its active and reactive parts. The given harmonic still might bear some nonzero reactive component (and a negative active component), but does not contribute to these power components anymore.

The IEEE powers are easier to decipher. The capacitiveness / inductiveness of the appliance can be determined from the sign of the reactive power, while the nonactive power is given by overall efficiency of the appliance (and is always non-negative). From the current distortion power D_I and voltage distortion power D_V the distortion of these quantities can be easily determined, although in the case of voltage it cannot be told whether the distortion is caused by the appliance or would be present in the grid even if the load was disconnected.

Main goal of our work was to correctly implement calculation of the IEEE definitions and the CPC theory. Further we want to concentrate on detailed experimental comparison of these two approaches. Our analysis will find its use in automatic intelligent detection of changes of power consumption, and for analysis and design of advanced compensation strategies.

ACKNOWLEDGMENT

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