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Three- phase four-wire circuits interpretation by means of different power theories

***Abstract**. In order to contribute to the discussion of defining a generalized power theory, valid for unbalanced and non linear circuits, this paper discusses the relationship and discrepancies among four modern power theories. Three-phase four-wire circuits have been analyzed, since the most conflicting and intriguing interpretations take place in case of return conductor occurrence. Simulation results of different load, power supply and line conditions will be discussed in order to elucidate the author's conclusions and to provoke the readers for additional discussions.*

Streszczenie.** Przedmiotem artykułu są wzajemne powiązanie i rozbieżności pomiędzy czterema aktualnymi teoriami mocy obwodów nieliniowych i niezrównoważonych. W artykule analizowane są obwody trójfazowe, czteroprzewodowe, gdyż najwięcej różnic interpretacyjnych pojawia się w związku z obecnością przewodu zerowego. Aby pobudzić dyskusję, w artykule przedstawiono wyniki modelowania różnych obciążeń i źródeł zasilania. **(Interpretacja obwodów trójfazowych, czteroprzewodowych za pomocą różnych teorii mocy).

Keywords: Non Sinusoidal Systems; Power Factor; Power Theories; Unbalanced Circuits.
Słowa kluczowe: niesinusoidalne, współczynnik mocy, teorie mocy, obwody niezrównoważone.

Introduction

The search for a general applicable power theory, suitable for analysis, revenue metering or power conditioning applications has been an intriguing subject during, at least, the last 100 years. This pursuit has been motivated in the last decades by the increasing use of non linear and unbalanced load, and more recently, it has been boosted up based on the novel configurations of modern power grids, especially those with relatively low short circuit levels (such as those related to micro and smart grids).

Nevertheless, even considering the great number of important contributions [1-9], there is not a final agreement on the voltage and current decompositions and the related power definitions, which should be adopted, especially in case of multiphase circuits with return conductor [11-17].

As discussed in [13-15,17], in case of four wire circuits, some of the confusion can be explained in terms of the choice of the voltage referential and also in terms of the return conductor impedance. Moreover, most of the misunderstanding is probably based on the fact that several authors had addressed their contributions for a specific application (power conditioning, revenue metering, etc.), instead of discussing a general applicable power theory.

However, an important query remains: what is expected from a general applicable power theory? Such issue has been investigated during the last several decades and the answer is still under construction [4]. Thus, considering the need of defining a generalized power theory, the authors of this paper call the attention to a number of relevant questions, which they believe are connected to the answer of the previous query.

- **Q1** Is there a more efficient domain for the analysis of power circuits, time or frequency? Which and why?
- **Q2** Is it necessary to split the voltages and currents into their fundamental and harmonic components? How?
- **Q3** Is it necessary and possible to relate the new concepts to the traditional and well accepted ones? How?
- **Q4** Is it possible to define and associate current and power components with specific physical phenomena?
- **Q5** Should different disturbing components, from different physical phenomena, be summed up into a non active current or power component? Why and how?
- **Q6** How to use the active and non active current and/or power components for revenue metering, power conditioning and responsibilities assessment?
- **Q7** What can be done in order to maintain the efficiency of the power system as good as possible in terms of ideal energy generation, transmission and consumption?
- **Q8** How to deal with multiphase circuits with return conductors? Is it a special case in multiphase systems?
- **Q9** Is it possible to use the same methodology to analyze load phenomena, as well as the entire power system?
- **Q10** Is it possible or is it time to employ the novel definitions in fundamental electrical engineering courses, such as Electrical Circuits?

The only certainty is that the conventional theory is no longer able to stand for the modern non linear and/or unbalanced multiphase power circuits. Thus, assuming that answering all the previous questions has been an extremely complex work and it will certainly take some time (years or decades), but trying to contribute to the discussion of defining a generalized power theory, this paper discusses and compares the results of four modern power theories, under different conditions. The investigated proposals were the so-called STD-1459, the FBD Theory (Fryze-Buchholz-Dependbrock), the p-q Theory and the Conservative Power Theory (CPT). It is important to state that the choice of these four proposals is based on a sequential work which has been realized by the authors. Other relevant proposals, especially the CPC (Currents' Physical Components) [4], are going to be included in future analyses.

Differently from [17], in this paper the authors are mostly interested in the interpretation of the power components, instead of current parcels. Further, the STD 1459 has been added to the comparative analysis. Next section shows the most relevant power components and their respective nomenclature, for each method.

Essential definitions of the investigated power theories

In order to avoid being repetitive in terms of overview, the authors refer to the original papers mentioned afterward, for additional details. It is important to notice that all the proposals are intrinsically based on multiphase conceptions.

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The IEEE Standard 1459-2010 [1,15,18]

Accordingly to the STD-1459, the interpretation of any three-phase power circuit can be done by means of the following power components:

P_{STD}	active power;
P_1	fundamental active power;
P_1^+	fundamental positive-sequence active power;
P_H	harmonic active power;
Q_1^+	fundamental positive-sequence reactive power;
D_{eI}	current distortion power;
D_{eV}	voltage distortion power;
S_1	effective fundamental apparent power;
S_1^+	positive sequence apparent power;
S_{U1}	fundamental unbalanced apparent power;
S_{eH}	effective harmonic apparent power;
S_{eN}	non fundamental apparent power;
S_e	total effective apparent power;
D_{eH}	non active harmonic apparent power;
N_{STD}	non active power;
PF_e	effective power factor (P_{STD} / S_e);
PF_1	fundamental power factor (P_1 / S_1);
PF_1^+	fundamental positive-sequence power factor (P_1^+/ S_1^+).

The FBD theory [2,3]

From the FBD current and power decompositions, the following components can be considered for the interpretation of multiphase circuits:

$P_{\Sigma a}$	collective rms active power;
$P_{\Sigma z}$	collective rms zero power component;
$P_{\Sigma v}$	collective rms variation power component;
$P_{\Sigma n}$	collective rms non active power component;
S_{Σ}	collective (total) apparent power;
PF_{Σ}	collective power factor ($P_{\Sigma a} / S_{\Sigma}$).

The p-q theory [5-7]

Accordingly to the *p-q* Theory, the following power components could be calculated in case of three-phase four wire circuits:

$p_{\alpha\beta}$	instantaneous real power;
p_0	instantaneous zero-sequence power;
$q_{\alpha\beta}$	instantaneous imaginary power;
$P_{\alpha\beta}$	average value of ($p_{\alpha\beta}$);
P_0	average value of (p_0);
$Q_{\alpha\beta}$	average value of ($q_{\alpha\beta}$);
$p_{\alpha\beta\sim}$	oscillating part of the real power;
$p_{0\sim}$	oscillating part of the zero-sequence power;
$q_{\alpha\beta\sim}$	oscillating part of the imaginary power;
$P_{\alpha\beta\sim}$	rms value of ($p_{\alpha\beta\sim}$);
$P_{0\sim}$	rms value of ($p_{0\sim}$);
$Q_{\alpha\beta\sim}$	rms value of ($q_{\alpha\beta\sim}$).

For the purpose of comparisons, the above power terms are not sufficient and it has been necessary to define in this paper, the apparent power and power factor, as following:

$$S_{\alpha\beta 0} = \sqrt{\left(P_{\alpha\beta} + P_0\right)^2 + Q_{\alpha\beta}^2} \tag{1}$$

and

$$PF_{\alpha\beta} = \frac{P_{\alpha\beta} + P}{S_{\alpha\beta 0}}. \tag{2}$$

The CPT theory [8-10]

Considering the CPT proposal, the following power components could be used for the interpretation of three-phase four wire circuits:

P_{CPT}	active power;
Q_{CPT}	reactive power;
S_{CPT}	modulus of the complex power;
PF_{CPT}	conventional power factor (P_{CPT}/S_{CPT});
V	void power;
N_a	unbalanced active power;
N_r	unbalanced reactive power;
N_{CPT}	unbalance power;
A	apparent power;
λ	total power factor (P_{CPT}/A).

Considerations regarding to the voltage referential

Above and beyond numerous particular details of the previous power components calculation, it is important to point out that the voltage referential was chosen according to each author's suggestion, i.e., for the FBD method is a virtual star point and for the other three methods, it is the return conductor (load side), as shown in Fig. 1.

Comparative analysis of STD, FBD, PQ and CPT proposals - simulation results

Fig. 1 and Table 1 illustrate the simulated power circuit, on which eleven different loads, supply and line impedances have been imposed. In the sequel, the simulated cases have been discussed in order to evaluate and compare the considered power theories. Tables 2 and 3 show the results of different power components, from each power theory, accordingly to the defined cases.

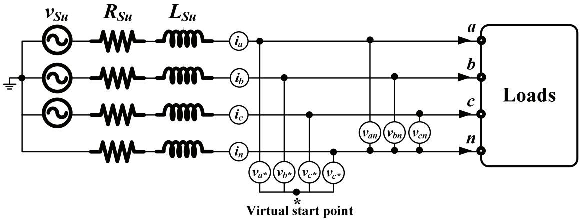

Fig.1. Simulated power circuit

Table 1. Load and line impedance's conditions

Case	Load configuration
A.1	7Ω (a-n), 14Ω (b-n), 15Ω (c-n)
A.2	160uF (a-b)
A.3	400uF (a-n)
A.4	400uF (a-n), 400uF (b-n), 800uF (c-n)
A.5	400uF
A.6	15Ω-2350uF (DC)
A.7	15Ω-2350uF (DC),15Ω-2350uF (DC), 7.5Ω-20uF (DC)
B.1	7Ω
B.2	7Ω-10mH
C.1	7Ω-5mH, 14Ω-8mH, 15Ω-3mH, $R_{S\mu}$ = 1Ω, $L_{S\mu}$ = 4mH
C.2	15Ω-2350uF (DC), $R_{S\mu}$ = 500mΩ, $L_{S\mu}$ = 2mH

Sinusoidal and balanced (127Vrms, 60Hz) voltages with neglected line impedance (strong grid)

Three-phase unbalanced resistive load - (A.1)

This simple case points for interesting discussions. The STD represents the load unbalance by means of S_{U1} and N components, indicating that part of the *effective apparent power* (S_e) is not related to active power. So, in this case, the *effective power factor* (PF_e or PF_1) is smaller than one, what in some way contradicts the conventional sense of unitary PF for single-phase resistive loads. However, if just positive sequence were considered, the PF_1^+ would be unitary, indicating the absence of energy storage element. In this case, the non fundamental and distortion power should be zero. The nonzero values are related to computation errors (smaller than 1%).

Applying the FBD, it is possible to notice that the collective active and apparent power exactly match the active and effective apparent power from the STD. The same happens with the PF_{Σ}, what means that the load unbalance has been considered as a non active power. Indeed, the load unbalance affects $P_{\Sigma z}$, $P_{\Sigma v}$ and $P_{\Sigma n}$.

Now assuming the p-q Theory, it is possible to observe that $P_{\alpha\beta}+P_0$ is equal to the active power from STD and FBD, while the imaginary average power is practically zero. In this case, the load unbalance could be observed by means of the instantaneous oscillatory behavior of real and imaginary power, as well as it could be estimated in terms of their RMS values ($P_{\alpha\beta}\sim$, $P_0\sim$, $Q_{\alpha\beta}\sim$).

Considering the CPT, it is possible to observe that the active power matches P_{STD}, $P_{\Sigma a}$ and ($P_{\alpha\beta}+ P_0$), from the other methods. The conventional power factor (PF_{CPT}) is unitary. Given that there are no distorted voltages and currents, the distortion power components are zero, however, the resistive load unbalance reflects in the unbalanced active power (N_a). Note that the unbalanced reactive power is zero, since there are no energy storage elements in the circuit. Such unbalance power (N_{CPT}) influences the apparent power (A), as well as the total power factor (λ), which is smaller than one, representing the part of the currents that circulates in the resistive circuit, but does not contribute to average active power (P_{CPT}).

Finally, other interesting comparisons could be pointed out, e.g.: the sum of the RMS real and imaginary oscillating components (from p-q Theory) results equal to the unbalanced active power from the CPT ($P_{\alpha\beta}\sim + P_0\sim + Q_{\alpha\beta}\sim = N_a$). Considering the apparent power results, it is possible to observe that the CPT value does not match the effective or collective values from FBD or STD ($S_e = S_\Sigma \neq A$), as well as the total power factor. It happens particularly in case of four-wire circuits, since the FBD and STD apparent power definitions, as discussed in [1-3,13,14], intrinsically considers the power phenomena from the power system's point of view, while the CPT addresses to the load point of view [16]. In case of four wire circuits, it means that any kind of homopolar power component, associated to the return conductor, is considered by STD and FBD approaches, while the CPT considers just the load aspects.

Single phase to phase capacitive load - (A.2)

The idea of this case has been extracted from [7], on which the authors discuss the potential of the p-q Theory in order to interpret the related physical phenomena by means of the instantaneous real and imaginary powers. Such authors call the attention to the fact that the instantaneous real power is different from zero, representing the oscillating energy flow during the charges and discharges of the capacitor, according to their terminal voltages. Moreover, the average power components $P_{\alpha\beta}$ and P_0 results zero (Table 2), while the $Q_{\alpha\beta}$ results equal (in modulus) to the reactive power from STD and CPT proposals.

If the goal is to analyze the physical phenomena by means of the power components, it is interesting to observe that $P_{\alpha\beta}\sim$ matches N_a from the CPT and $P_{\Sigma v}$ from FBD (all related to active instantaneous currents), while $Q_{\alpha\beta}\sim$ matches N_r from the CPT (both related to reactive instantaneous currents). It makes sense if one considers the unbalanced behavior of this phase-phase capacitive load, in terms of the three-phase circuit.

The understanding of this case is based on the observation of each phase, as well as, the three-phase instantaneous power components from the p-q and CPT methods. Even if the capacitive load does not draw any three-phase active power (P), the instantaneous power, per phase, could be decomposed into active and reactive (or imaginary) components, as well as it leads to oscillatory behavior over the three-phase instantaneous components. In terms of the power phenomena interpretation, such oscillatory behavior is considered by means of the rms oscillatory components in the p-q method, as well as the N components in the CPT, the non active power in the FBD and the S_{U1} in the STD. The apparent power matches for STD, FBD and CPT proposals and all power factors indicate zero value.

It is also interesting to observe the negative signal of the reactive power components, for the CPT and p-q Theory, indicating capacitive behavior, such as in the conventional conception. The reactive and zero power components from STD and FBD will always result positive, in consequence of their formulations.

Single phase to neutral capacitive load - (A.3)

In this case, the CPT and STD reactive power components are equivalent and match the imaginary power from p-q Theory. Considering the CPT, it is worth to notice that the unbalance reactive power (N_r) is even greater than the balanced reactive power (Q). Besides, in the same way of case A.1, the apparent power from the CPT does not match the FBD and STD values. Observe that in this case, the influence of the homopolar components is quite severe, since it deals with a single phase load in the three-phase four-wire circuit.

Three-phase (Y connection to neutral) unbalanced capacitive load - (A.4)

Again, the CPT and STD reactive power components are equivalent and match the imaginary power from p-q Theory. Besides, ($P_{\alpha\beta}\sim + Q_{\alpha\beta}\sim = N_r$). Similar to A.1 and A.3, due to the homopolar behavior of the four-wire unbalance circuit, the apparent power from the CPT does not match the FBD and STD values.

Considering the FBD, in addition to the apparent power that matches the STD definition, the variation power ($P_{\Sigma v}$) is equal to the oscillating power components from the p-q Theory. In this case, the whole FBD power is interpreted like non active power ($P_{\Sigma n}$), in terms of the zero power ($P_{\Sigma z}$) and variation power ($P_{\Sigma v}$) components.

Three-phase (Y connection to neutral) balanced capacitive load - (A.5)

In this case, all the reactive (CPT and STD), imaginary (p-q), zero and non active (FBD) power components are equivalent. The same happens with the apparent power components ($S_e = S_\Sigma = A$), given that the load is balanced. Besides, both the unbalance (N_{CPT}), variation ($P_{\Sigma v}$) and rms values of the oscillating powers (p-q) results null.

Three-phase balanced non linear load (three phase to neutral diode rectifiers with RC load) – (A.6)

Considering such balanced non linear load, observe that the active power components are equal for all methods. The same happens to the values of Q_{CPT}, $Q_{\alpha\beta}$ and Q_1^+. The modulus of the complex power (S_{CPT}) from the CPT also matches the p-q apparent power ($S_{\alpha\beta}$), as well as the (S_1^+) from STD. The rms value of the oscillating real power ($P_{\alpha\beta}\sim$) is equal to the variation power ($P_{\Sigma v}$) from FBD. The non active components from STD and FBD are also equivalent ($N_{STD} = P_{\Sigma n}$). In addition, notice that the unbalance power components from CPT (N_{CPT}) and STD (S_{U1}) are about zero, since the load is balanced. In this case, the STD and CPT represent the load nonlinearities by means of the distortion power (D_{eI}) and void power (V) components, respectively.

Based on the observation that this non linear load, even if balanced, leads to neutral (homopolar) currents, over again, the CPT apparent power does not match the effective or collective values from FBD or STD ($S_e = S_\Sigma \neq A$). However, it can be noticed that regardless of of the neutral current, P_0 and $P_0\sim$ results zero, given that the voltages are sinusoidal and balanced (strong grid).

Three-phase unbalanced non linear load (three phase to neutral diode rectifiers with RC load) – (A.7)

One can observe again that the active power components from the four methods are equivalent, as well as the reactive and imaginary components from STD, CPT and p-q Theory. Moreover, the modulus of the complex power (S) from the CPT matches again the p-q apparent power ($S_{\alpha\beta}$) and the (S_1^+) from STD.

Considering the CPT, notice that the unbalanced behavior of the load appears at the active and reactive unbalanced power components (N_a and N_r). On the other hand, the load nonlinear behavior results in the occurrence of void power (V). Note that since the line impedance is neglected, the voltages are not affected by the load and the voltage distortion power (D_{eV}), from the STD is zero. As in the previous case, it is possible to observe the difference between the conventional (PF) and the total power factor (λ). Additionally, the rms value of the oscillating real power ($P_{\alpha\beta}\sim$) is equal to the variation power ($P_{\Sigma v}$). The non active components from STD and FBD are also equivalent ($N_{STD} = P_{\Sigma n}$).

Nonsinusoidal and balanced (127Vrms, 60Hz; 12.7Vrms, 180Hz; 6.35Vrms, 300Hz; 6.35Vrms, 420Hz) voltages with neglected line impedance (strong grid)

Three-phase balanced resistive load (B.1)

This other very simple case also points for interesting discussion. Note that the p-q and CPT are practically equivalents. Although a slightly oscillatory behavior of the instantaneous power (caused by the instantaneous product of distorted voltages and currents), which can be observed by means of $P_{\alpha\beta}\sim$ and $P_0\sim$, both methods indicates an equivalent average active power ($P_{\alpha\beta} + P_0 = P_{CPT}$), which also corresponds to the active power from STD and FBD. In case of the CPT, the decompositions indicate that there is no unbalance component (N_{CPT}), what makes sense in case of balanced load. Moreover, there is no void power (V), what means that the total apparent power is conveyed into active power on the balanced resistive load.

On the other hand, the STD proposal suggests the power decomposition into several fundamental and harmonic power components, as e.g., the harmonic active power (P_H).

Regarding to STD and FBD, it is interesting to observe that the total apparent powers (S_e, S_Σ) practically match and they are greater than the CPT apparent power. This occurs since the imposed supply voltages have homopolar components, resulting in return conductor current circulation, even if the load is balanced.

It is valid to mention that the interpretation of non active and non fundamental components from STD and FBD and their relation with physical phenomena is not so intuitive in this case.

Three-phase balanced RL load (B.2)

In this case, all the active power components results equal (P_{CPT}, P_{STD}, $P_{\alpha\beta} + P_0$, $P_{\Sigma a}$). The same happens with the reactive power from CPT, STD and p-q Theory, which have practically the same values.

Besides, the inductive (RL) behavior of the load leads to a non linear condition, with different distorted phase voltages and currents. In this case, the CPT suggests the existence of void power (V), which is mainly related to the non linearity of phase voltages and currents [9,10]. There is no unbalance power (N_{CPT}).

It is also possible to observe that the modulus of the complex power from CPT is approximately equal to the values of ($S_{\alpha\beta}$) and (S_1^+), from p-q Theory and STD. Besides, the non active components from FBD ($P_{\Sigma n}$) and STD (N_{STD}) practically match.

Table 2. Power components for cases A.1 to A.7

FBD	A.1	A.2	A.3	A.4	A.5	A.6	A.7
$P_{\Sigma a}$	4551	0	0	0	0	5563	5870
$P_{\Sigma z}$	2540	3590	5729	11061	7329	12748	9747
$P_{\Sigma v}$	847	2073	1727	1728	0	5461	4812
$P_{\Sigma n}$	2678	4146	5984	11195	7329	13869	10870
S_Σ	5281	4146	5984	11195	7329	14943	12354
PF_Σ	0.862	0	0	0	0	0.372	0.475

STD	A.1	A.2	A.3	A.4	A.5	A.6	A.7
P_{STD}	4551	0	0	0	0	5563	5870
P_1	4551	-1	-1	3	1	5562	5870
P_1^+	4551	0	-1	2	1	5562	5870
P_H	0	1	1	-3	-1	1	0
Q_1^+	4	2931	2443	9772	7329	2177	1572
DeI	4	4	2	10	5	13697	10649
DeV	2	1	2	4	3	2	2
S_1	5279	4146	5984	11196	7329	5973	6261
S_1^+	4551	2931	2443	9772	7329	5973	6077
S_{U1}	2675	2932	5463	5465	6	14	1506
S_{eH}	0	0	0	0	0	5	4
S_{eN}	5	4	3	11	6	13697	10649
S_e	5281	4146	5984	11195	7329	14943	12354
D_{eH}	0	0	0	0	0	5	4
N_{STD}	2678	4146	5984	11195	7329	13869	10870
PF_e	0.862	0.000	0.000	0.000	0.000	0.372	0.475
PF_1	0.862	0.000	0.000	0.000	0.000	0.931	0.938
PF_1^+	1.000	0.000	0.000	0.000	0.000	0.931	0.966

PQ	A.1	A.2	A.3	A.4	A.5	A.6	A.7
$P_{\alpha\beta}$	4551	0	0	0	0	5563	5870
P_0	0	0	0	0	0	0	0
$Q_{\alpha\beta}$	0	-2931	-2443	-9771	-7329	-2174	-1569
$P_{\alpha\beta}\sim$	847	2073	1727	1727	0	5461	4812
$P_0\sim$	0	0	0	0	0	0	0
$Q_{\alpha\beta}\sim$	847	2073	1727	1727	0	2988	2660
$S_{\alpha\beta0}$	4551	2931	2443	9771	7329	5973	6076
$PF_{\alpha\beta}$	1.000	0.000	0.000	0.000	0.000	0.931	0.966

CPT	A.1	A.2	A.3	A.4	A.5	A.6	A.7
P_{CPT}	4551	0	0	0	0	5563	5870
Q_{CPT}	0	-2931	-2443	-9771	-7329	-2174	-1569
S_{CPT}	4551	2931	2443	9771	7329	5973	6076
PF	1.000	0.000	0.000	0.000	0.000	0.931	0.966
V	0	0	0	0	0	8716	7119
N_a	1694	2073	0	0	0	0	432
N_r	0	2073	3455	3455	0	0	857
N_{CPT}	1694	2931	3455	3455	0	0	960
A_{CPT}	4856	4146	4231	10364	7329	10566	9408
λ	0.937	0.000	0.000	0.000	0.000	0.527	0.624

Sinusoidal and balanced (127Vrms, 60Hz) voltages with high line impedance (weak grid)

Three-phase unbalanced RL load - (C.1)

Despite of the active power components, which result in equivalent values (P_{CPT}, P_{STD}, $P_{\alpha\beta} + P_0$, $P_{\Sigma a}$), each method represents the power phenomena in a different way. But it is important to observe that in the case of high line impedance, the load voltages suffer the influence of the load current and consequently, it will influence various power components.

The CPT indicates active and reactive load behavior, as well as, it points to non zero unbalance power components (because of the line impedance influence on the load voltages). The p-q Theory represents the unbalanced load by means of the rms values of the oscillatory power components. Considering the FBD, it points to the zero, variation and non active power to represent the load unbalances and reactive behavior. Finally, the STD represents the load performance by means of its several power components, indicating no distortion power, but reactive and unbalance behavior.

Table 3. Power components for cases B.1, B.2, C.1 and C.2

FBD	B.1	B.2	C.1	C.2
$P_{\Sigma a}$	7047	5404	3289	3875
$P_{\Sigma z}$	1043	2990	1506	2781
$P_{\Sigma v}$	37	247	588	852
$P_{\Sigma n}$	1044	3000	1617	2908
S_{Σ}	7124	6181	3665	4845
PF_{Σ}	0.989	0.874	0.897	0.799

STD	B.1	B.2	C.1	C.2
P_{STD}	7047	5404	3289	3875
P_1	6943	5382	3289	3941
P_1^+	6943	5382	3334	3941
P_H	104	23	0	-66
Q_1^+	3	2899	711	1184
DeI	1473	746	4	2442
DeV	694	611	1.5	838
S_1	6943	6113	3669	4115
S_1^+	6943	6113	3669	4115
S_{U1}	3	4	1355	9.8
S_{eH}	147	75	0	492
S_{eN}	1635	967	4.3	2629
S_e	7132	6189	3669	4884
D_{eH}	104	71	0	493
N_{STD}	1103	3016	1626	2972
PF_e	0.988	0.873	0.897	0.793
PF_1	1.000	0.880	0.897	0.958
PF_1^+	1.000	0.880	0.978	0.958

PQ	B.1	B.2	C.1	C.2
$P_{\alpha\beta}$	6977	5385	3317	3936
P_0	69	19	-27	-61
$Q_{\alpha\beta}$	0	2897	737	1218
$P_{\alpha\beta\sim}$	25	225	524	539
$P_{0\sim}$	49	26	35	212
$Q_{\alpha\beta\sim}$	0	363	656	613
$S_{\alpha\beta 0}$	7047	6131	3371	4062
$PF_{\alpha\beta}$	1	0.881	0.976	0.954

CPT	B.1	B.2	C.1	C.2
P_{CPT}	7047	5404	3289	3875
Q_{CPT}	0	2910	643	1078
S_{CPT}	7047	6138	3352	4022
PF	1.000	0.880	0.981	0.963
V	0	538	0	2013
N_a	0	0	1123	0
N_r	0	0	473	0
N_{CPT}	0	0	1218	0
A_{CPT}	7047	6171	3566	4506
λ	1.000	0.876	0.922	0.859

Three-phase balanced non linear load (three phase to neutral diode rectifiers with RC load) – (C.2)

In this case it is interesting to observe that the resulting unbalance power components from the CPT and STD are equal to zero. On the other hand, the load current distortion results in voltage distortion by means of the line impedance, producing voltage distortion power (STD), as well as to the void power (CPT).

Except for the active power definitions, which still match, one may notice that in this case, with high line impedance (weak grid), the comparisons of all other power components does not points to any numerical equivalence. It is also very interesting to point out the differences among the power factor definitions in cases C.1 and C.2. The choice of one or other could result in very different efficiency interpretation.

Conclusions

The previous discussions indicate that the understanding of physical phenomena can be very characteristic, depending on the adopted methodology. Nevertheless, it was also possible to identify a number of similarities among the investigated power theories, as well as discussed in [19]. In some cases, the definitions are equivalent or they could be complementary.

From the point of view of quantifying the influence of specific disturbing components, the STD and CPT seem to be more suitable. However, it is important to point out that the FBD and STD formulations seem to be mainly related to the characterization of the network utilization (including sources, loads and transmission lines), while the CPT and p-q seem to be essentially related to the load phenomena.

Such difference can be mostly relevant in case of four-wire circuits, because of the homopolar current circulation and it may stimulate several discussions on which should be the most relevant approach. However, the authors believe that it is just a question of *what are we interested in*? Are we interested in analyzing, penalizing or compensating *the load* or *the overall network*? One or other approach should be used or modified in order to satisfy the application. For example, the CPT apparent power could be easily modified to match the STD and FBD proposals, by means of changing the voltage referential and some equations to consider the voltage and the current of return conductor [10].

Moreover, for the purpose of contributing to answer the questions of Section I and considering the forthcoming definitions of a general applicable power theory, these authors would state:

- Q1 – No. It is possible to represent the power phenomena in both, time and frequency domains, since using the correct mathematical tools and theoretical theorems. However, some physical phenomena could be easily considered by means of one or other domain, such as in case of scattered current and power definitions, using the frequency domain [4];
- Q2 – Basically, it depends on the application. It could be necessary, e.g., for compensation or revenue metering. In this case, some kind of signal processing technique should be applied. Possible formulations splitting fundamental and harmonic components can be found in [1,10];
- Q3 – Yes, in some cases. From the analyses of the CPT and STD power components, one can observe several similarities with traditional or cognitive conceptions and it certainly helps during the argumentation process of defining new quantities. The simplest idea is to make use of the novel definitions to explain very basic conditions;
- Q4 – Yes. It can be observed, e.g., in case of the distortion, void and unbalanced components from the CPT and STD, which are strictly related to physical phenomena. In case of identifying specific current and power terms associated to particular phenomena, it is important to point out that the resulting components should be preferentially orthogonal among themselves;
- Q5 – It depends on the application. If one is interested in compensating the non active components (non selectively), e.g., by means of electronic apparatus, this could be necessary. However, if one is interested in the interpretation of different physical phenomena or interested in penalizing different non ideal effects, it should not be done. In this sense, the CPT and STD would be preferable;
- Q6 – In case of active power components, it has been demonstrated that all the formulations results identical

and they could be applied to energy calculation as in the common sense. Considering the non active components, a number of new indexes should be defined in order to evaluate the *load performance* or the *network utilization*. For example, it could be defined some void or unbalance factors directly from the power components (e.g., V_{CPT}/A_{CPT} or N_{CPT}/A_{CPT} from the CPT or similar relations from STD), which could be limited by specific standards, as in case of the power factor. The same components or their respective voltage and current signals could be used for power conditioning. The issue of responsibilities assessment could be explored in terms of the different power components, as well as the values of the line impedance, which is responsible for the interaction among loads and the network. In this case, the STD and CPT seem to point in a more suitable point of view. At this point, it is essential to call attention to the importance of using orthogonal current and power terms, avoiding e.g., penalization duplicity;

- Q7 – The total power factor, as defined in the FBD and STD should be assured unitary. It would represent a highly efficient load, in terms of power conversion, and minimal losses in the power system;
- Q8 – Yes. The authors believe that it is a special case and the return conductor should not be treated as an ordinary phase conductor. The condition of four-wire circuits leads to an important difference in terms of the analysis of the load or network point of view. Depending on the application, the suitable methodology should be adopted;
- Q9 – No. As discussed above, although the various similarities among the addressed power theories, it is possible to observe that the FBD and STD seem to be more convenient for the analysis of the power system, while the CPT and PQ regards to the load phenomena interpretation;
- Q10 - Yes, it is possible and it should be time of incorporating novel definitions on the fundamental courses, avoiding the situation on teaching traditional concepts based on sinusoidal and balanced conditions, which in practice, did not exist anymore in real applications.

Finally, assuming the increasing importance of micro grid applications for modern smart grid, on which the line impedance is expected to be higher than in case of traditional (strong) power systems, the definitions of novel power components will be a very important issue. As indicated in the previous analysis, the case of high line impedance and non linear load can be very difficult to be understood, even if considering the novel power theories formulations evaluated in this paper.

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