CHARACTERIZATION OF NON-LINEAR THREE-PHASE UNBALANCED CIRCUITS POWERS FLOW SUPPLIED WITH SYMMETRICAL VOLTAGES

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Key words: Three-phase unbalanced circuits, Țugulea power theory, Non-linear loads, Non-sinusoidal regime, Non-symmetry active power, Residual (distorting) active power, Non-symmetry reactive power, Residual (distorting) reactive power, Symmetry power factor (SPF), Non-symmetry power factor (NPF), Distorting power factor (DPF).

The present study continues the research presented in a previous article by the same authors focussed on the power theory of Professor Andrei Țugulea, dedicated to non-linear three-phase unbalanced circuits. The defined symmetry, non-symmetry and residual (distorting) active and reactive powers flow and conservation are further investigated in three-phase circuits with neutral. Correspondingly, the original theory introduced the symmetry power factor (SPF), the non-symmetry power factor (NPF) and the distorting power factor (DPF) as suitable quantities for characterizing such three-phase circuits (with or without neutral). The paper proves the validity of the theory extended to three-phase circuits with zero impedance neutral on test-circuits simulated in PSpice software. The resulting data are used in a dedicated software usable in on-line or off-line calculations, as well as on power grid automated management.

1. INTRODUCTION

Professor Țugulea’s three-phase theory represents a synthesis of interesting concepts and observations gathered in a suite of published articles dating back to the 1980’s [1–5]. Its aggregation followed essentially two main steps. First, a single-phase circuit containing among others a non-linear (distorting) load was under scrutiny. Supplied with a purely sinusoidal voltage, the only source of current harmonics, and hence voltage harmonics throughout the network, results to be the non-linear load. Correspondingly, the conservative residual (distorting) active and reactive powers were introduced for the voltage and current superior harmonics.

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Secondly, a linear unbalanced three-phase load, component of a larger circuit supplied with symmetrical voltages was considered. Here, the Fortescue decomposition allows to prove that the unbalanced load plays the same role as the non-linear load before. Unwanted non-symmetry active and reactive powers components are re-injected into the grid by the unbalanced load increasing losses and overall consumption. Combining the two effects, it results that a parasitic power flow occurs as a result of the presence of an unbalanced and non-linear load in a three-phase network supposedly containing only linear and balanced loads. Although small and therefore difficult to put in evidence in practice by measurement, the residual (distorting) and non-symmetry powers become important over a long period of time with regard to consumers’ energy measurement and billing. It results as a fact that, in what concerns the active power, the linear and balanced consumers are additionally charged due to the unwanted parasitic powers originated from the non-linear and unbalanced loads. Specific power factors were defined to provide a rapid and comprehensive outlook of the described phenomena [3, 4]. As proved in [4], the essence of this approach relies in the conservative nature of the active and reactive powers as they were defined by Budeanu [6], according with Tellegen’s theorem [7], which is based on the topological properties of Kirchhoff’s node and loop theorems [8]. Almost a decade later a further refinement of the theory took shape [9, 10]. In [10] a first experiment on a physical circuit seeking validation of the theory was reported.

Nowadays, many of the domestic and industrial loads are both non-linear and unbalanced, making this issue important from the above-described phenomena perspective. To better assess this issue, the authors have revisited from today’s perspective Professor Țugulea’s power theory, aiming to take full advantage of the now existing data acquisition and processing hardware and software capabilities. In our previous work [11] a software module was designed to compute in real-time or as post-processing unit the symmetry, non-symmetry and residual active and reactive powers in neutral isolated three-phase circuits. Validation of this approach, but also of the theory itself, was realized on three test-circuits simulated in Orcad PSpice 16.6 Lite environment. The use of some other software based on time or frequency domain methods is also possible [12, 13]. A full validation obtained through calculus concerns all the aforementioned powers, showing that non-symmetry and residual active are “generated” and re-injected into the grid by the unbalanced, non-linear load. In contrast with that, non-symmetry and residual reactive powers are proved to be bidirectional.

The present study focuses on the study of the three-phase circuits with neutral, realizing a software for powers and power factors computation. It also extends the interpretation of the results presented in [11] from the perspective offered by the power factors and total harmonic distortion (THD) values.
2. SYMMETRY, NON-SYMMETRY AND DISTORTING POWER FACTORS IN THREE-PHASE ISOLATED NEUTRAL CIRCUITS

The symmetry, non-symmetry and residual power factors definitions is based on the determination of the homologues active powers and the direct sequence apparent power corresponding of the fundamental (“fundamental apparent power of symmetry” [9]).

In [11], without any loss of generality, a simple three-phase network without neutral containing four components was used to illustrate the definition and the symmetry, non-symmetry and residual powers and their flow, as follows: a symmetrical generator (SG) having two linear balanced consumers (the power line –BLℓ and a load –BLL) and a unbalanced non-linear load (UNL).

According to [9, 11], two formally identical sets of balance relations can be written:

\[
\begin{align*}
P_G &= P_{G,s} = P_{r,s} + P_{L,s} + P_{N,s} \\
0 &= P_{r,n} + P_{L,n} + P_{N,n} \\
0 &= P_{r,r} + P_{L,r} + P_{N,r} \\
\end{align*}
\]

(1)

and

\[
\begin{align*}
Q_G &= Q_{G,s} = Q_{r,s} + Q_{L,s} + Q_{N,s} \\
0 &= Q_{r,n} + Q_{L,n} + Q_{N,n} \\
0 &= Q_{r,r} + Q_{L,r} + Q_{N,r} \\
\end{align*}
\]

(2)

where \( P_G = P_{G,s} \) is the active power delivered by the SG (only on the fundamental positive sequence and thus equal to the symmetry active power); \( P_{L,s}, P_{L,r}, P_{N,s} \) are the symmetry active powers (corresponding to BLℓ, BLL and UNL) also as the fundamental positive sequence absorbed power active power; \( P_{L,n}, P_{L,n}, P_{N,n} \) represent the same receptors’ non-symmetry active powers (the sum of the fundamental negative and zero components active powers); \( P_{r,s}, P_{r,n}, P_{r,r} \) are the residual (distorting) active powers of the three loads – the active power of the harmonics with \( h > 0 \), including here the dc component. Similar, reactive power quantities can be defined: \( Q_G = Q_{G,s} \) the reactive power delivered by the SG; \( Q_{L,s}, Q_{L,n}, Q_{N,s} \) are the symmetry reactive powers; \( Q_{L,n}, Q_{L,n}, Q_{N,r} \) non-symmetry reactive powers; \( Q_{r,s}, Q_{r,n}, Q_{N,r} \) are the residual (distorting) reactive powers, all referring to BLℓ, BLL and UNL, respectively. The balance relationships from (1) and (2) are illustrated in Fig. 1. Assuming the passive sign convention for all the three loads it turns out that the non-linear, unbalanced load (UNL) acts like an active power generator (\( P_{N,s} < 0 \) and \( P_{N,r} < 0 \)) injecting both non-symmetry and residual (distorting) powers to the linear balanced loads (BLℓ, BLL).
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\[ nL, nN, PPP +⇒ A \] and \[ rL, rN, PPP + = A, \] as shown in Fig. 1a. For obvious reasons for the same reactive non-symmetry and residual (distorting) powers, the last two equalities do not hold, and the corresponding power flow is bidirectional, as shown in Fig. 1b. This last assumption was proved by calculus in [11] for test-circuit 3.

A global overview of the symmetrical powers, on one hand, and of the non-symmetry and residual (distorting), on the other hand, is facilitated by the definition of some corresponding power factors. Starting from the obvious relationship of the total active power \( r, n, s, PPP + = P_N, a, a \), a proposed power factor (PS) is defined for three-phase circuits [9], as follows:

\[ k_{P_a} = \frac{P_a}{S_a, a}, \text{ with } a \in \{\ell, L, N\}, \]  \( (3) \)

where \( S_a, a \) is the symmetry fundamental apparent power of each load. The symmetry powers are considered as having a privileged status among the rest, being the only directly transmitted to the loads, as shown in Fig. 1. In more detail we get:

\[ k_{P_a} = \frac{P_{a, s} + P_{a, n} + P_{a, d}}{S_{a, s}}, \text{ with } a \in \{\ell, L, N\}, \]  \( (4) \)

where \( k_{P_a}, k_{P_n, a}, k_{P_d, a} \) represent the symmetry, non-symmetry and distorting power factors, respectively.

Fig. 1 – Symmetry, non-symmetry and residual (distorting) powers flow in a simple three-phase network without neutral, containing a non-linear three-phase unbalanced load (UNL); a) active power; b) reactive power.
With the data presented in [11] for the test-circuits, we get the power factors shown in Table 1.

<table>
<thead>
<tr>
<th>Load /PF</th>
<th>Test-circuit 1</th>
<th>Test-circuit 2</th>
<th>Test-circuit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLℓ</td>
<td>0.927 0.004 0.037</td>
<td>0.787 0.175 0.497</td>
<td>0.538 0.028 0.05</td>
</tr>
<tr>
<td>BLL</td>
<td>0.863 0.003 0.029</td>
<td>0.954 0.017 0.028</td>
<td>0.999 0.009 0.005</td>
</tr>
<tr>
<td>UNL</td>
<td>0.938 -0.019 -0.190</td>
<td>0.218 -0.118 -0.070</td>
<td>0.223 -0.069 -0.078</td>
</tr>
</tbody>
</table>

The negative values highlighted in Table 1 not only indicate that UNL acts like a source for the two “parasitic” active powers, but also gives a quantitative indication (a ratio) with respect to the “legitimate” active power absorbed from the SG.

### 3. SYMMETRY, NON-SYMMETRY AND RESIDUAL POWERS AND CORRESPONDING POWER FACTORS FOR THREE-PHASE CIRCUITS WITH ZERO IMPEDANCE NEUTRAL

The aim of this section is to present the symmetry, non-symmetry and residual active and reactive powers, their conservative flow and the corresponding power factors for the three-phase circuits with neutral of zero impedance, shown in Fig. 2. At the same time, the further presented calculations will be implemented in a compact software as presented in [11]. In Fig. 2, BL, BLL and UNL, $k \in \{1, 2, 3\}$ are the phases of BL, BLL and UNL, respectively. Correspondingly, and currents associated with the passive sign convention there are the phase voltages: $v_{a,k}(t)$ and $i_{a,k}(t)$ with $a \in \{L, N\}$ and $k \in \{1, 2, 3\}$, also shown in Fig. 2. The symmetrical generator (SG) delivers at his terminals the following symmetrical sine wave voltages:

$$v_1(t) = V \sqrt{2} \sin \omega t, v_2(t) = V \sqrt{2} \sin(\omega t - 2\pi/3)$$
$$v_3(t) = V \sqrt{2} \sin(\omega t + 2\pi/3)$$  \hspace{1cm} (5)

where $V$ is the rms value of the phase voltages and $\omega$ is the angular frequency. Their corresponding complex phasors become $V_1, V_2$ and $V_3$. After performing a Fourier decomposition of all nine phase voltages and nine phase currents, we denote their fundamental components as $\{v_{a,1}(t), v_{a,2}(t), v_{a,3}(t)\}$ and $\{i_{a,1}(t), i_{a,2}(t), i_{a,3}(t)\}$ of complex phasors $\{V_{a,1}^{(1)}, V_{a,2}^{(1)}, V_{a,3}^{(1)}\}$ and $\{I_{a,1}^{(1)}, I_{a,2}^{(1)}, I_{a,3}^{(1)}\}$ with $a \in \{L, N\}$. Let $\{V_a^{(0)}, V_a^{(\omega)}, V_a^{(-\omega)}\}$ and $\{I_a^{(0)}, I_a^{(\omega)}, I_a^{(-\omega)}\}$ be the fundamental phase voltages and currents Fortescue components.
The total complex power developed by the SG, only delivered on the positive sequence becomes [8, 11]:

\[ S_G = P_G + jQ_G = P_{G,s} + jQ_{G,s} = 3V_s^*(I_t^{(*)}) = 3V_s^{(*)}I_t^{(*)}, \]  

where the superscript * symbol stands for complex conjugate. Therefore, the total active and reactive powers coincide to the symmetry active and reactive powers \( P_{G,s} \) and \( Q_{G,s} \), respectively. Similarly, we get with symmetry and non-symmetry complex apparent powers

\[ S_{a,s}^{(l)} = P_{a,s} + jQ_{a,s} = 3V_s^{(*)}I_a^{(*)}, \]  

and

\[ S_{a,n}^{(l)} = P_{a,n} + jQ_{a,n} = 3V_a^{(-)}I_a^{(-)} + 3V_a^{(0)}I_a^{(0)} \text{ for } a \in \{r, l, N\}, \]  

whose real and imaginary parts correspond to symmetry and non-symmetry powers of all the loads.

The residual (distortion) active and reactive powers are defined as:

\[ P_{a,r} = \sum_{k=1}^{1} V_a^{(0)}I_a^{(0)} + \sum_{h=2}^{g} V_a^{(h)}I_a^{(h)} \cos \phi_{a,h}, \]
\[ Q_{a,x} = \sum_{k=1}^{3} \sum_{h=2}^{\infty} V_{a,k}^{(h)} I_{a,k}^{(h)} \sin \phi_{a,k}^{(h)} \text{ for } a \in \{\ell, L, N\}, \quad (10) \]

where \( V_{a,k}^{(h)} \) and \( I_{a,k}^{(h)} \) are the rms (including dc components in (9)) values of \( v_{a,k}^{(h)}(t) \) and \( i_{a,k}^{(h)} \), \( \phi_{a,k}^{(h)} \) the corresponding phase-shift, with \( a \in \{\ell, L, N\}, k \in \{1, 2, 3\} \) and \( h = 0, 2, 3, \ldots \) the harmonic order.

The three power factors are the same as in (3) and (4).

On the basis of equations (1) – (10) a compact calculation program, suitable either for “on-line” (real-time) calculations (applicable on power grid management) or for “off-line” determinations (as the those performed on the test-circuit simulations results presented in the next chapter).

4. CIRCUIT TEST-MODEL SIMULATION

In order to give a qualitative and quantitative interpretation of all the parameters presented in Chapters 2 and 3, three test-circuits were imagined and then analyzed with Orcad Lite 16.6 PSpice component, which provides as output data the Fourier analysis (amplitude and angle) of \( v_{a,k}^{(h)}(t) \) and \( i_{a,k}^{(h)} \) for \( a \in \{\ell, L, N\}, k \in \{1, 2, 3\} \) and \( h = 0, 1, 2, \ldots \) (all voltages and currents are shown in Fig. 2). Data for the simulated circuits are as follows [11]:

- **Test-circuit 1** (shown in Fig. 3a): \( R_\ell = 200 \, \Omega \), \( L_\ell = 250 \, \text{mH} \); \( R_L = 300 \, \Omega \), \( L_L = 550 \, \text{mH} \); \( R_{N1} = 100 \, \Omega \), \( R_{N2} = 300 \, \Omega \), \( R_{N3} = 500 \, \Omega \); \( D_1 \) and \( D_3 \) are diodes.

![Fig. 3a – Three-phase test-circuit 1 (with diodes and non-linear inductances).](image_url)
Fig. 3 b – **Test-circuit II** (with thyristors and non-linear inductances).

- **Test-circuit 2** (shown in Fig. 3b): \( R_{\ell} = 10 \, \Omega \), \( L_{\ell} = 25 \, \text{mH} \); \( R_{N1} = 5 \, \Omega \), \( R_{N2} = 1 \, \Omega \), \( R_{N3} = 10 \, \Omega \); \( T_{11}, T_{21}, T_{31} \) and \( T_{32} \) are thyristors forming two triacs with various conduction angles.

- **Test-circuit 3** (similar to the circuit shown in Fig. 3b, except inductances \( L_{\ell} \) which are all replaced with capacitances \( C_{\ell} \)): \( R_{\ell} = 10 \, \Omega \), \( C_{\ell} = 0.2 \, \text{mF} \); \( R_{N1} = 5 \, \Omega \), \( R_{N2} = 1 \, \Omega \), \( R_{N3} = 10 \, \Omega \); \( T_{11}, T_{21}, T_{31} \) and \( T_{32} \) are thyristors having the same role as above.

All three circuits supplied at \( f = 50 \, \text{Hz} \), \( V = 230 \, \text{V} \) the rms value of the symmetrical voltage system; non-linear inductances in [mH] are defined as:

\[
L_{N1}(i) = 0.5(i^2 + i + 1), \quad L_{N2}(i) = 2.5(i^2 + i + 1), \quad L_{N3}(i) = 5(i^2 + i + 1),
\]

with \( i \) given in amperes. The \( i \)-polynomial coefficients from the parenthesis are given respectively in \( A^{-2}, A^{-1} \) and the last one is dimensionless. Results are concerning powers and power factors are presented in Table 2 – Table 5.

### Table 2

Results and power balance for **test-circuit 1** (dc and 15 harmonic components were considered)

<table>
<thead>
<tr>
<th>Load /Power</th>
<th>( P_s ) [W]</th>
<th>( P_d ) [W]</th>
<th>( P_f ) [W]</th>
<th>( P_{\text{total}} ) [W]</th>
<th>( Q_s ) [var]</th>
<th>( Q_d ) [var]</th>
<th>( Q_f ) [var]</th>
<th>( Q_{\text{total}} ) [var]</th>
<th>( I_{\text{total}} ) [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL(\ell)</td>
<td>173.98</td>
<td>1.74</td>
<td>6.01</td>
<td>181.73</td>
<td>70.56</td>
<td>0.71</td>
<td>0.56</td>
<td>71.83</td>
<td></td>
</tr>
<tr>
<td>BLL</td>
<td>90.39</td>
<td>1.00</td>
<td>3.88</td>
<td>95.27</td>
<td>53.38</td>
<td>0.57</td>
<td>0.39</td>
<td>54.34</td>
<td></td>
</tr>
<tr>
<td>UNL</td>
<td>65.79</td>
<td>-2.71</td>
<td>-9.77</td>
<td>53.31</td>
<td>32.34</td>
<td>-1.28</td>
<td>-1.00</td>
<td>30.06</td>
<td></td>
</tr>
<tr>
<td>Sum [W] / [var]</td>
<td>330.16</td>
<td>0.03</td>
<td>0.13</td>
<td>330.31</td>
<td>156.28</td>
<td>0.002</td>
<td>-0.04</td>
<td>156.23</td>
<td></td>
</tr>
<tr>
<td>Balance relative error [%]</td>
<td>–</td>
<td>-0.96</td>
<td>-1.29</td>
<td>–</td>
<td>0.13</td>
<td>4.50</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>335.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>158.48</td>
<td></td>
</tr>
</tbody>
</table>
Table 3

Results and power balance for **test-circuit 2** (dc and 50 harmonic components were considered)

<table>
<thead>
<tr>
<th>Load /Power</th>
<th>$P_s$ [W]</th>
<th>$P_n$ [W]</th>
<th>$P_d$ [W]</th>
<th>$P_{total}[W]$</th>
<th>$Q_s[\text{var}]$</th>
<th>$Q_n[\text{var}]$</th>
<th>$Q_d[\text{var}]$</th>
<th>$Q_{total}[\text{var}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLℓ</td>
<td>1020.22</td>
<td>282.37</td>
<td>28.30</td>
<td>1350.89</td>
<td>797.69</td>
<td>215.53</td>
<td>74.41</td>
<td>1087.63</td>
</tr>
<tr>
<td>BLL</td>
<td>1309.11</td>
<td>80.01</td>
<td>60.52</td>
<td>1449.63</td>
<td>−409.57</td>
<td>−25.22</td>
<td>−4.09</td>
<td>−438.88</td>
</tr>
<tr>
<td>UNL</td>
<td>797.77</td>
<td>−361.85</td>
<td>−88.61</td>
<td>347.31</td>
<td>2124.53</td>
<td>−185.24</td>
<td>−69.88</td>
<td>1869.40</td>
</tr>
<tr>
<td>Sum [W] / [var]</td>
<td>3127.10</td>
<td>0.53</td>
<td>0.21</td>
<td>3127.84</td>
<td>2512.64</td>
<td>5.07</td>
<td>0.44</td>
<td>2518.15</td>
</tr>
<tr>
<td>Balance relative error [%]</td>
<td>−0.15</td>
<td>−0.24</td>
<td>−</td>
<td>−</td>
<td>−2.74</td>
<td>−0.62</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>SG</td>
<td>3144.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4

Results and power balance for **test-circuit 3** (dc and 50 harmonic components were considered)

<table>
<thead>
<tr>
<th>Load /Power</th>
<th>$P_s$ [W]</th>
<th>$P_n$ [W]</th>
<th>$P_d$ [W]</th>
<th>$P_{total}[W]$</th>
<th>$Q_s[\text{var}]$</th>
<th>$Q_n[\text{var}]$</th>
<th>$Q_d[\text{var}]$</th>
<th>$Q_{total}[\text{var}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLℓ</td>
<td>1429.10</td>
<td>246.06</td>
<td>94.28</td>
<td>1769.44</td>
<td>2221.13</td>
<td>80.27</td>
<td>3.43</td>
<td>2644.84</td>
</tr>
<tr>
<td>BLL</td>
<td>2414.75</td>
<td>172.54</td>
<td>22.82</td>
<td>2610.11</td>
<td>−125.78</td>
<td>−8.88</td>
<td>−0.36</td>
<td>−135.03</td>
</tr>
<tr>
<td>UNL</td>
<td>822.06</td>
<td>−423.19</td>
<td>−112.70</td>
<td>286.16</td>
<td>2687.43</td>
<td>−88.36</td>
<td>46.98</td>
<td>3122.78</td>
</tr>
<tr>
<td>Sum [W] / [var]</td>
<td>4665.91</td>
<td>−4.59</td>
<td>4.39</td>
<td>4665.72</td>
<td>340.52</td>
<td>−0.79</td>
<td>3.19</td>
<td>342.92</td>
</tr>
<tr>
<td>Balance relative error [%]</td>
<td>−1.08</td>
<td>−3.90</td>
<td>−</td>
<td>−</td>
<td>−2.0</td>
<td>6.79</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>SG</td>
<td>4709.98</td>
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<td></td>
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</tr>
</tbody>
</table>

Table 5

Symmetry, non-symmetry and distortion PFs for test-circuits with neutral

<table>
<thead>
<tr>
<th>Load /PF</th>
<th>$k_s$</th>
<th>$k_n$</th>
<th>$k_d$</th>
<th>$k_s$</th>
<th>$k_n$</th>
<th>$k_d$</th>
<th>$k_s$</th>
<th>$k_n$</th>
<th>$k_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLℓ</td>
<td>0.927</td>
<td>0.009</td>
<td>0.032</td>
<td>0.788</td>
<td>0.218</td>
<td>0.022</td>
<td>0.541</td>
<td>0.093</td>
<td>0.036</td>
</tr>
<tr>
<td>BLL</td>
<td>0.861</td>
<td>0.010</td>
<td>0.037</td>
<td>0.954</td>
<td>0.058</td>
<td>0.044</td>
<td>0.999</td>
<td>0.071</td>
<td>0.009</td>
</tr>
<tr>
<td>UNL</td>
<td>0.897</td>
<td>−0.037</td>
<td>−0.133</td>
<td>0.352</td>
<td>−0.159</td>
<td>−0.039</td>
<td>0.293</td>
<td>−0.151</td>
<td>−0.040</td>
</tr>
</tbody>
</table>

Fig. 4 a – The most distorted voltage and current waveforms of **test-circuit 1**.
In order to provide an insight concerning the voltage and current magnitudes and waveforms, the most distorted voltages and currents (all from phase 1 – UNL) of test-circuits I–III are shown in Fig. 4, including the corresponding THD value. The time span corresponds to two periods of the voltages supplied by the SG, sufficiently long time after the beginning of the transient analysis. The necessity of introducing the dc power component into the residual active power becomes now evident (at least at a theoretical and definition level), as depicted in Fig. 4a, where both voltage and current possess an important dc component and associated power.

5. CONCLUSIONS

The results obtained for the three-phase test-circuits with neutral (simulating low-voltage distribution networks) are consistent with Professor Ţugulea’s general power theory, providing an additional proof of its validity. Similar to [11], the symmetry, non-symmetry and residual active and reactive powers flow were put in evidence through circuit numerical analysis and software analytical computation performed by a dedicated module created by the authors. An additional feature of this software module is that it not only provides access (in real-time or as post-processor) to the above-mentioned active and reactive powers flowing in a given three-phase network, but also to some more descriptive quantities, namely the symmetry, non-symmetry and distorting power factors. The use of these power factors in an automated grid management systems can provide additional information to the process, with important outcomes.
Even very small in practice for a single given device, the phenomena associated to non-symmetry and residual active and reactive powers, summed up for a large number of network components over a long period of time, have a non-negligible impact in what concerns overall energy consumption and, finally, the greenhouse gas emissions on a global scale.

Last but not least, the present work pleads for future standardization of the presented powers and power factors, as the appropriate theoretical background to address the ever increasing power efficiency and quality challenges [14] of modern transport and distribution networks.

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REFERENCES