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DEMONSTRATING THE SYMMETRY AND NON-SYMMETRY COMPONENTS BALANCE IN GRIDS WITH NEUTRAL CONDUCTOR

IONUT-MARIUS MINDREANU[1], RADU-MIRCEA CIUCEANU[2], IOSIF VASILE NEMOIANU[2,*]

Keywords: Distribution grid; Active power; Reactive power; Unbalanced consumers; Nonlinear consumers; Symmetrical components power theory (SCPT); Powers of symmetry; Powers of non-symmetry; Residual (distorting) powers; Waveforms; Harmonics; Total harmonic distortion (THD).

In the context of the ever-increasing complexity of modern power systems, optimizing consumers' performance to improve electrical energy quality becomes paramount. This article thoroughly examines the power transfer effects in the context of distorting and non-symmetrical regimes in three-phase, four-wire power systems, focusing on heavily nonlinear and unbalanced consumer influence across the grid. Particular emphasis is placed on the impact of these regimes on the parasitic active and reactive powers affecting linear and balanced consumers due to distorting and unbalanced ones. An essential aspect of this analysis is including the neutral conductor in the experimental circuit, enhancing relevance and a more profound understanding of consumer interactions in modern networks. Quantitative aspects of the phenomena involved are assessed from the perspective offered by SCPT (introduced by Andrei Ţugulea), allowing us to identify the source of non-symmetry and residual powers through comprehensive power balance equations for the active and reactive powers.

1. INTRODUCTION

Non-symmetrical and distorting consumers present a significant challenge in managing energy efficiency and the stability of electrical systems. Harmonic distortions and phase imbalances can lead to considerable energy losses and strain critical electrical network components [1–10]. This paper aims to apply the symmetrical components power theory (SCPT), introduced by Andrei Ţugulea – introduced in the seminal articles [11–15] and reviewed experimentally in [19]. The main objective is to put evidence and investigate the energy effects of distortion and non-symmetry regimes through experiments (Fig. 1) [19].

The presence of the neutral wire in the circuit allows for a particular perspective on the impact of imbalances and distortions on the system. The neutral wire plays a crucial role in stabilizing voltages and reducing the adverse effects of non-symmetry regimes, thus improving the quality of the supplied energy. The study examines how these imbalances and distortions can influence not only energy efficiency but also the operational stability of the power system. The present paper is a follow-up of [19], using a similar laboratory platform in which the neutral conductor is present, further investigating the influence of various nonlinear and unbalanced circuit configurations on the unwanted active and reactive powers.

Through such detailed analysis, the article offers valuable insights for optimizing and more effectively managing modern electrical networks, considering the need to ensure reliable and high-quality power supply for all consumers, regardless of their level of disturbance.

The conservation and circulation of power in unbalanced and heavily distorting three-phase networks are critical for ensuring efficient and stable operation.

Under these conditions, managing efficient power flows becomes complex due to harmonic distortions and phase imbalances.

In any electrical system, the principle of power conservation must be observed. This means that the balance equations for the active and reactive powers must be verified, regardless of the consumers' distortions or imbalances [20], an aspect representing one pillar on which SCPT relies. We consider the main power quantities in which this theory operates, namely their definitions reviewed in [19], which are eq. (1) – (11). A special mention must be made for the powers of non-symmetry ([19], eq. (8) and (9)), which effectively contain the zero sequence components due to the presence of the neutral, unlike the 3-wire circuits. For the experimental circuits, analyzing these power components involves precise measurements and rigorous interpretation of the results, allowing us to understand the unwanted effects produced in the presence of imbalances and distortions [11–19], as detailed in chapters 2 and 3.

Fig. 1– Physical implementation of the laboratory platform [19].

2. ANALYZED EXPERIMENTAL CIRCUITS

There are two proposed models for studying the importance of the neutral conductor in a circuit with unbalanced electrical loads and nonlinear elements that introduce higher-order harmonics into the network.

The first proposed model includes two nonlinear elements connected to the distorting 3-phase load, one on phase-1 and one on phase-2, while two capacitors are connected in parallel for phase-3. The second consumer is a balanced load without nonlinear elements, thereby highlighting the circulation of electrical power between the circuits'

[1] Doctoral School of Electrical Engineering, National University of Science and Technology Politehnica Bucharest, 313 Splaiul Independenței, 060042 Bucharest, Romania. E-mail: ionut.mindreanu@stud.electro.upb.ro.
[2] Faculty of Electrical Engineering, National University of Science and Technology Politehnica Bucharest, 313 Splaiul Independenței, 060042 Bucharest, Romania. E-mail: radu.ciuceanu@upb.ro.
[*]Corresponding author, E-mail: iosif.nemoianu@upb.ro.

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connected consumers due to the nonlinear elements and the imbalances (Fig. 2).

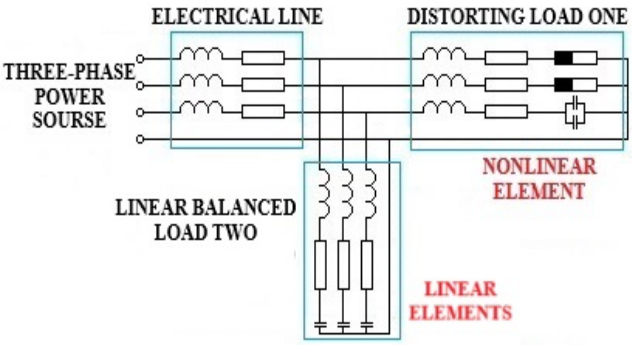


Fig. 2 – Circuit diagram with multiple nonlinear elements mounted on the first and second phases of the distorting load one in a circuit with neutral (MODEL ONE).

In the second proposed model there is an imbalance for both consumers, which all distort. One nonlinear element is connected to the phase-1 at the first distorting consumer, and the second nonlinear element is connected to the phase-3 at the second distorted consumer. Additionally, at the first distorting consumer, there are also two capacitors connected in parallel on the phase-3 and an inductor connected on the phase-2, to purposely inflict significant imbalance to the load, as shown in Fig. 3.

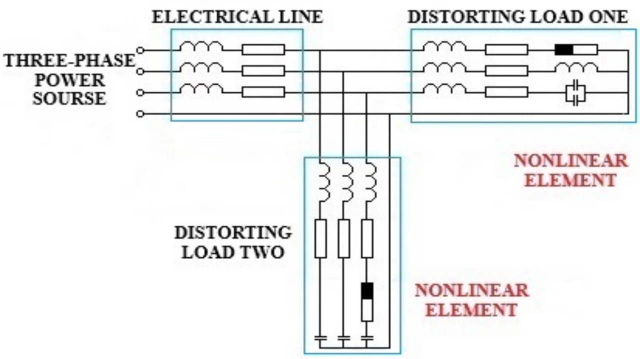


Fig. 3 – Circuit diagram comprising two distorting three-phase loads; the two unequally distorting nonlinear elements are mounted on phase-1 of the first load and phase-3 of the second load (MODEL TWO).

The same block diagram was maintained for both models: a symmetrical voltage source and two 3-phase consumers; only the component elements for the two consumers were modified. Thus, for the first model, one consumer is distorted, and the second is balanced and linear, whereas for the second model, both consumers are distorted and unbalanced.

3. MEASUREMENTS, RESULTS, AND DISCUSSIONS

The measurements were based on four Janitza UMG 509-PRO network analyzers for the synchronous acquisition of voltage and current waveforms at various critical points in the network, as highlighted in the upper left section of Fig. 1 [19]. These analyzers can monitor and record voltage and current variations with high accuracy, allowing for a detailed assessment of the circuits' behavior under nonlinear and unbalanced load conditions.

To graphically illustrate the waveforms of voltage or current and generate histograms of the corresponding harmonic content, a Chauvin Arnoux C. An 8336 network analyzer, visible in the central-left section of Fig. 1, was used. This device specializes in capturing and analyzing higher-order harmonics, thereby providing a detailed representation of the harmonic distortions generated by the nonlinear elements in the network.

3.1. CIRCUIT MODEL ONE

Measurements for the first model are acquired at three important points for the proposed determinations and the configuration of the experimental circuit. The first acquisition is made at the circuit's power source terminals. The distorted waveforms for phases 1 and 2, where the two nonlinear elements are connected, show a third phase with reduced THD (Fig. 4).

The waveforms for the acquisition at the connection terminals of the first 3-phase consumer (distorting consumer, Fig. 5) are much more distorted and have a higher THD value, compared to the waveforms initially acquired. The THD corresponding to phase-2 is greater than the THD of phase-1, because the conduction angles of the nonlinear elements are different. Thus, each nonlinear element distorts differently, although they are of the same nature (voltage variators).

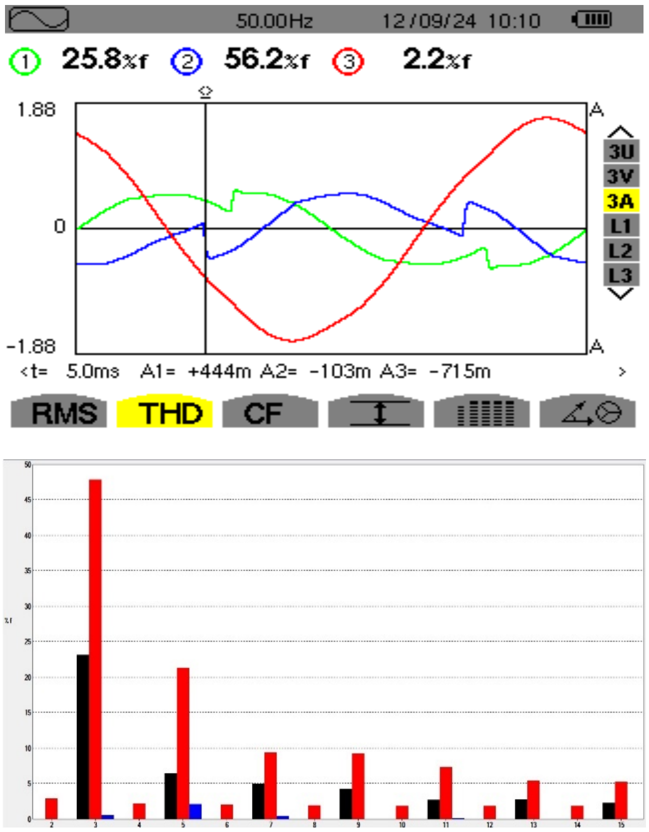


Fig. 4 – a) waveforms of the currents flowing along the electrical power line; b) the current harmonics before the connection point of the two distorting three-phase consumers.

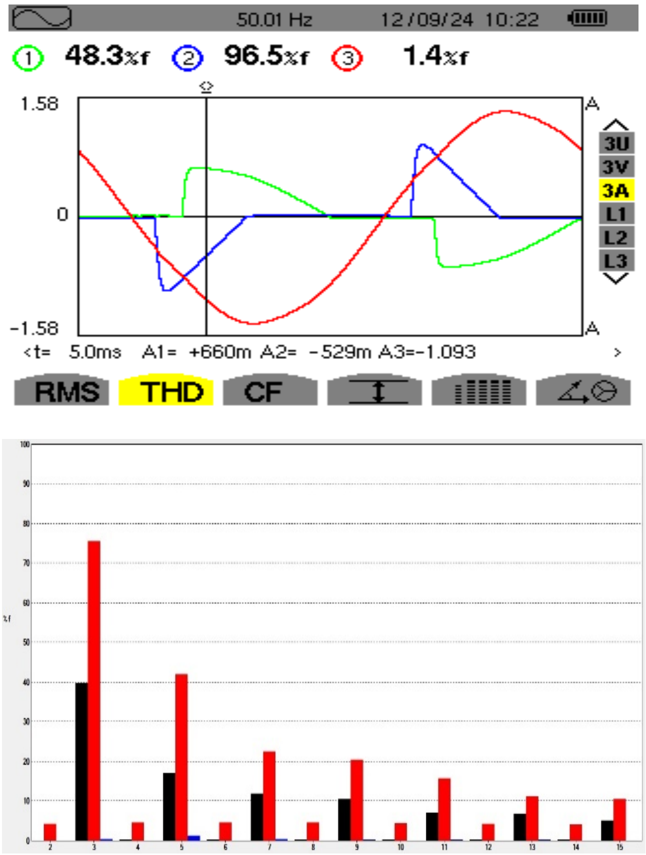


Fig. 5 – a) the waveforms of the currents for the three phases; b) the current harmonics at the terminals of distorting consumer one.

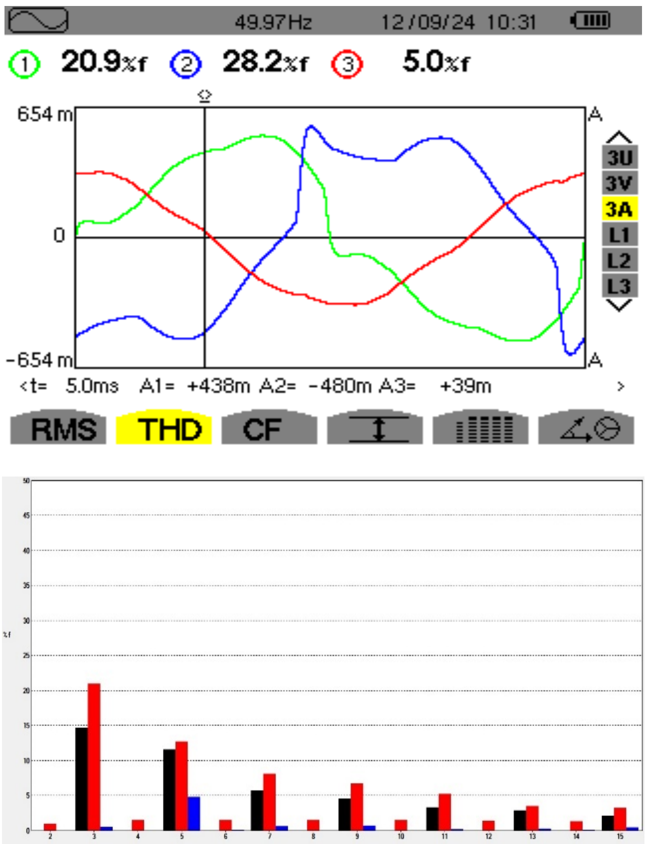


Fig. 6 – a) the waveforms of the currents for the three phases; b) the current harmonics at the terminals of distorting consumer two.

It can be observed that at the connection terminals of the second linear consumer, the waveforms are distorted. However, they are less distorted compared to the two previous data acquisitions, as shown in Fig. 6. The amplitude level of the harmonics is lower. As we get closer to the distorting point in the circuit, the level of distortion becomes more evident. The computed results are obtained in conditions similar to those in [19], and the same software was utilized. Also, the passive sign convention was considered for all the elements making up the circuit. The results obtained are organized in Table 1.

Table 1

Symmetry, non-symmetry, residual, and total active and reactive powers corresponding to circuit model one; power balance verification (Model 1).

	P_s [W]	P_n [W]	P_r [W]	P_{total} [W]
Power line	70.87	27.38	2.35	100.59
Consumer 1	148.88	-28.87	-3.60	116.41
Consumer 2	21.75	1.16	1.22	24.14
Sum [W]	241.50	-0.33	-0.04	241.13
3 ~ source	239.22			
Error [%]	-0.80	1.14	1.03	

	Q_s [var]	Q_n [var]	Q_r [var]	Q_{total} [var]
Power line	0.95	0.72	0.56	2.22
Consumer 1	-1.69	4.33	0.21	2.84
Consumer 2	-99.57	-5.23	-0.77	-105.56
Sum [var]	-100.32	-0.18	0.00	-100.49
3 ~ source	-100.41			
Error [%]	-0.09	3.36	0.19	

According to the obtained values, the first distorted consumer delivers non-symmetry and residual active power to the other two consumers. This additional active power in the circuit is partially received by the second linear consumer, while the electrical line receives the remainder. In other words, the second linear consumer is overloaded with this additional active power, which is recorded by the measuring device and supplementarily billed as qualitatively suggested in Fig. 7).

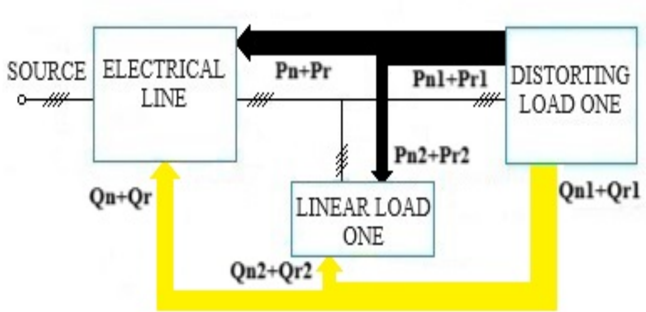


Fig. 7 – Non-symmetry and residual active and reactive powers' flow (MODEL ONE).

The Țugulea theory predictions concerning the non-symmetry and residual reactive powers are also confirmed in our experiment. The distorted consumer 1 has a robust capacitive characteristic. As a result, it delivers negative values of Q_{n1} and Q_{s1} powers, meaning that it absorbs reactive powers on the positive and zero sequences and the DC and upper harmonic components. Thus, it must be stressed that the delivered Q_{n1} and Q_{s1} powers shown in Fig. 7 are both hostile in the context in which the passive sign convention was used in the computation, as previously mentioned for the active power components.

3.2. CIRCUIT MODEL TWO

For the second model, where the two nonlinear elements are allocated one for each consumer, both consumers are therefore distorting. The data acquisition is performed at the same three points in the circuit, and the waveforms for the first measurement taken at the connection point of the two consumers are distorted (see Fig. 8), with the observation that the THD is low for the third phase.

The conduction angles for the two nonlinear elements also differ in the second model. The amplitude of the harmonics in the case of the first acquisition point is higher for phase-2. For the acquisition made at the connection point of the first distorting consumer, the amplitude of the harmonic corresponding to phase-1 is the highest, while for the harmonics acquired at the connection point of the second distorting consumer, the amplitude corresponding to phase-3 is more significant (see Figs. 9 and 10).

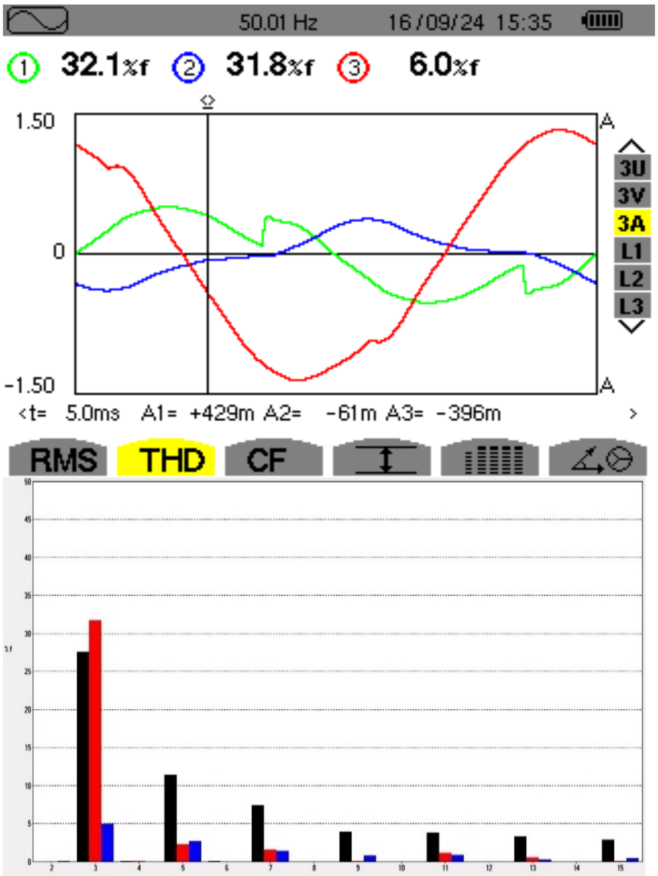
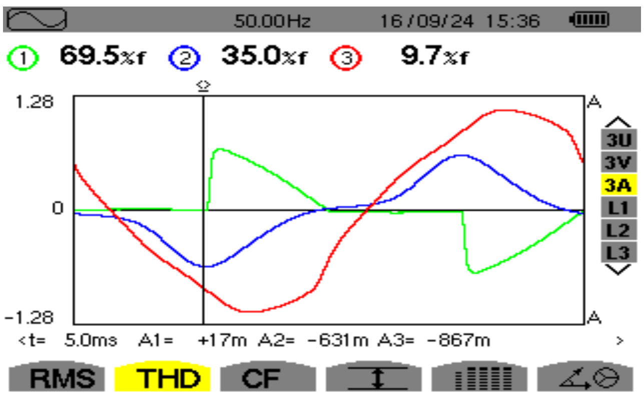


Fig. 8 – a) waveforms of the currents flowing along the electrical line; b) the current harmonics before the connection point of the two 3-phase consumers.



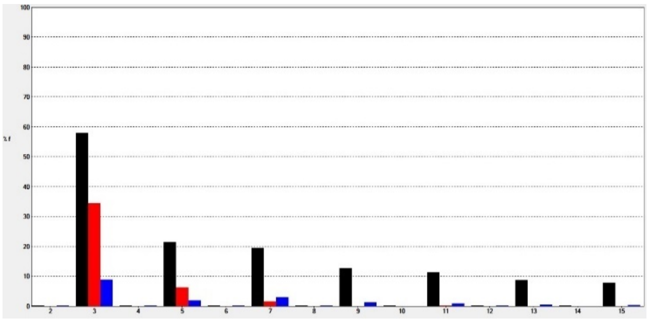


Fig. 9 – a) The waveforms of the currents for the three phases; b) the current harmonics at the terminals of load one.

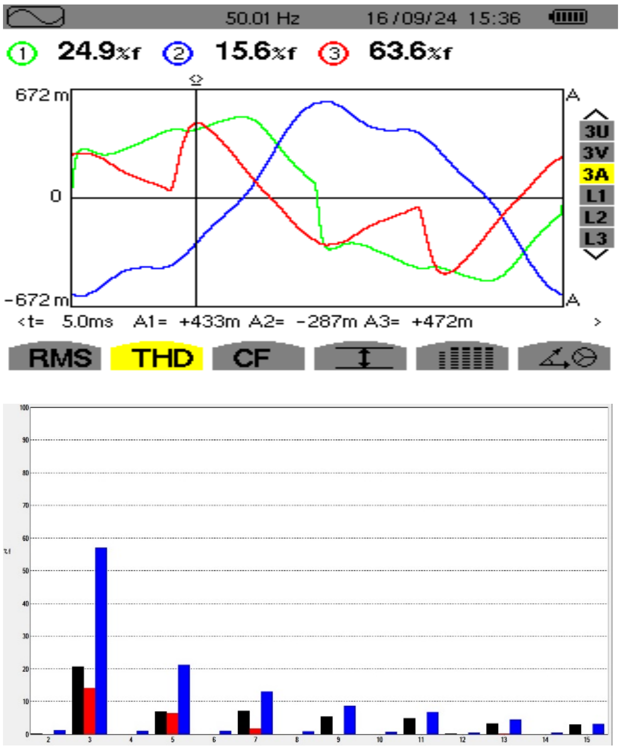


Fig. 10 – a) the waveforms of the currents for the three phases; b) the current harmonics at the supply terminals of load two.

Table 2

Symmetry, non-symmetry, residual, and total active and reactive powers corresponding to circuit model two; power balance verification (Model 2).

	P_s [W]	P_n [W]	P_r [W]	P_{total} [W]
Power line	64.28	30.34	1.71	96.33
Consumer 1	108.04	-29.10	-1.87	77.07
Consumer 2	35.04	-1.85	0.25	33.43
Sum [W]	207.36	-0.61	0.08	206.84
3 ~ source	204.81			
Error [%]	-0.99	-2.00	-4.42	
	Q_s [var]	Q_n [var]	Q_r [var]	Q_{total} [var]
Power line	1.27	0.72	0.32	2.32
Consumer 1	13.93	18.49	0.51	32.92
Consumer 2	-72.26	-19.41	-0.84	-92.51
Sum [var]	-57.06	-0.20	-0.01	-57.26
3 ~ source	-56.94			
Error [%]	-0.57	1.01	0.86	

In this studied case, the first more distorting consumer injects non-symmetry and residual active power into the system. The first distorting consumer also receives non-symmetry and residual reactive power, just like the electrical line, while the second distorting consumer delivers non-symmetry and residual reactive power to the first distorting consumer and the electrical line (Fig. 11 and Table 2).

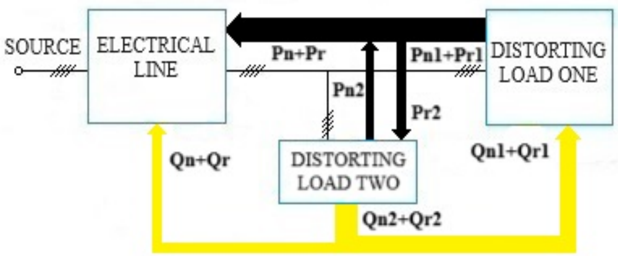


Fig. 11 – Non-symmetry and residual active and reactive powers' flow (MODEL TWO).

4. **CONCLUSIONS**

In the first experimental model, the nonlinear elements from the first consumer significantly affected the waveforms of the second consumer (the linear and balanced one). This negative influence on the waveforms clearly shows that the presence of nonlinear elements in a circuit introduces distortions and disturbances in the flow of electric currents and voltages.

In both models, there is an undesirable power circulation between the participants in the electric circuit. In the first model, the nonlinear distorting consumer induces the flow of parasitic active and reactive powers to the balanced and linear consumers. In the second model, where both consumers are nonlinear and unbalanced, the flow of electric power between these consumers is present and accentuated, indicating that the nonlinearity of both consumers amplifies these phenomena.

The experiments demonstrate that introducing nonlinear elements into an electric circuit can disrupt its balance, leading to distorted waveforms and unwanted electric power circulation between linear and nonlinear consumers, as predicted by Țugulea power theory, which is once more verified. These distorting effects suggest the need for careful management of nonlinear loads in electrical networks, especially in industrial or commercial applications.

The differences in the conduction angles of the nonlinear elements that were set suggest that this parameter plays a significant role in determining the magnitude and direction of the electric power flow in the circuit. Adjusting and controlling the conduction angle of the convertors could represent a method for mitigating disturbances and optimizing the performance of electrical circuits with nonlinear components.

Measurements show that as the acquisition point gets closer to the location of the nonlinear elements, the amplitude of the current harmonics and the THD level increase. This finding is relevant for the design of electrical networks, indicating the need for harmonic filtering solutions or other measures to reduce network distortions that include nonlinear loads.

The second experimental model, in which both consumers are nonlinear and unbalanced, suggests that the distribution of nonlinearities in the circuit influences how power circulates between consumers. This distribution can generate additional instabilities and imbalances to the power. It underscores the importance of detailed analysis and careful optimization of the configurations of electrical networks where distributed nonlinear loads are present.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ionuț-Marius Mîndreanu: formal analysis, literature investigation, data acquisition, data organization, writing – original manuscript preparation.
Radu-Mircea Ciuceanu: measurement methodology, experimental platform design, measurement supervision, data consistency analysis and verification.
Iosif Vasile Nemoianu: conceptualization, software development, writing – manuscript review and editing, funding, and procurement.

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