SIMULATION OF THREE-PHASE DISTRIBUTION SYSTEMS WITH UNBALANCED NONLINEAR LOADS, USING PSPICE

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***Abstract* – This paper presents a new proposal for simulations of three-phase distribution systems with unbalanced non-linear loads, using PSpice. An electrical model of transformer with Δ/Y connection is employed in the simulation, providing conditions for the analysis of multi-lines representations, including the evaluation of harmonic contents in the currents and voltages of each phase. The nonlinear loads are represented as equivalent harmonic current sources (harmonic Norton method), which are connected in parallel with an R-L combination representing the linear portion of the total load.**

***Keywords* – Three-Phase Distribution Systems, PSpice, Unbalanced Nonlinear Loads**

I. INTRODUCTION

The simulation is an important tool for the prediction of the effects from the growth of nonlinear loads connected to the electrical energy distribution systems [1 until 10]. This approach permits the development of several analyses concerning Power Quality topics, such as: propagation of distorted currents in the distribution lines, and harmonic distortions in the voltages applied to coupling points.

In the literature, it is usual to find analyses of three-phase distribution systems based on their one-line diagrams [1]. However, it is necessary to assume that the systems are supplying only balanced loads. Moreover, considering transformers with Δ/Y connections, the presence of balanced loads implies in the confinement of *triplens* from the load currents (third-order harmonic components and their multiples) into the Δ connection. So, as a consequence of these one-line representations, the *triplens* will never flow through the primary line.

Unfortunately, these one-line representations are not suitable for the evaluation of real (and generic) three-phase distribution systems, which are usually unbalanced. Thus, the simulation of distribution systems based on multi-lines representations (three wires in the primary lines, and four wires in the secondary lines) can provide better results, because the subsequent analyses will be performed based on more accurate data regarding the effects of unbalanced and nonlinear loads. It is important to note that a proper model for the three-phase transformer is required for the development of simulations based on multi-lines representations [10].

According to this context, this paper presents a new proposal for simulations of distribution lines, based on multi-lines representations. A model of three-phase transformer with Δ/Y connection is used, providing conditions to emulate the electrical characteristics of a real device, namely: transforming ratio, and confinement of *triplens* into the Δ connection (considering only balanced loads). The Norton Method (Injection Current Method) is used for the obtaining of models of nonlinear loads [1 until 3]. In this method, the equivalent nonlinear loads can be represented by parallel-connected current sources, with amplitudes, phases, and frequencies specified according to the correspondent harmonic components of the real load.

II. SCHEMATIC DIAGRAM OF THE SIMULATED SYSTEM

Figure 1 shows the simplified unifilar diagram of the system. This diagram represents a real distribution line, which was reduced in order to simplify the analyses and the simulations. So, only essential points are represented in the Figure 1. The voltage supply of this system is considered as an ideal bus. The simplified system presents eight buses in the primary line.

A model of three-phase transformer, proposed in [10], is connected at P_6, as showed in Figure 1. This model is capable to emulate the electrical characteristics of a Δ/Y-grounded connection. Figure 2 shows the simplified schematic diagram of this model, implemented with controlled voltage and current sources, available in PSpice.

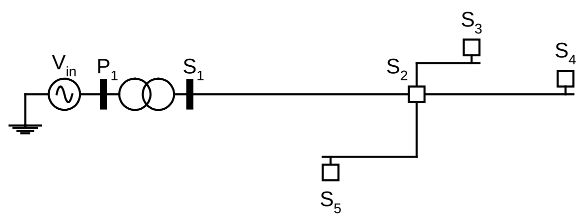
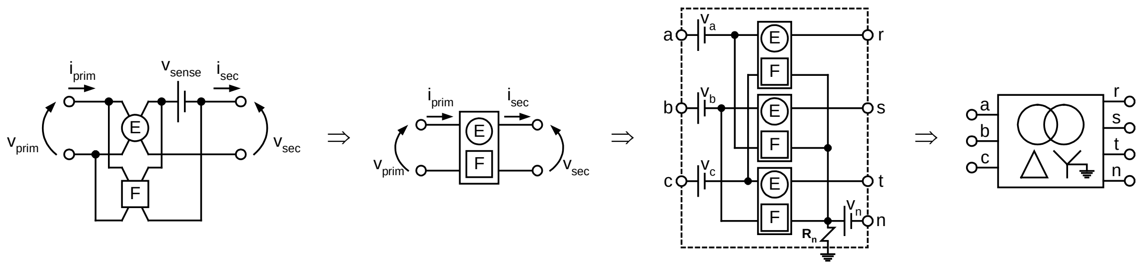


Fig. 1. Simplified unifilar diagram of the distribution line.



(a) (b) (c) (d)

Fig. 2. Model of three-phase transformer.

The voltage sources v_{pa}, v_{pb}, v_{pc}, and v_{sn} are used as sensors of line currents, and they are set to zero voltage. It is important to highlight that, according to [10], one of the major advantages of this three-phase transformer model is the evaluation of the effects produced by the connection of unbalanced nonlinear loads in the secondary.

The secondary of the transformer model is connected to a distribution line that presents three Load Concentration Points (LCP – S_3, S_4, and S_5). Sets of three-phase unbalanced nonlinear loads are connected to each point. Figure 3 shows the representation of these loads. The voltage sources v_r, v_s, v_t, and v_n, showed in Figure 3.b, are sensors of current and are set to zero voltage.

The schematic diagram simulated in PSpice is showed in Figure 4. The primary line is not considered in this analysis because the main objective of this work is to evaluate only the influence of the nonlinear loads on the system (voltage distortion in the secondary and current distortion in the primary). Ideal voltage sources are used to supply the system, which means that v_A, v_B and v_C present no distortion.

III. DATA

Tables I and II show a summary of the data employed in the simulation.

The parameters of secondary lines (Table I) are calculated according to the specifications of the cables and the distances between the LCPs.

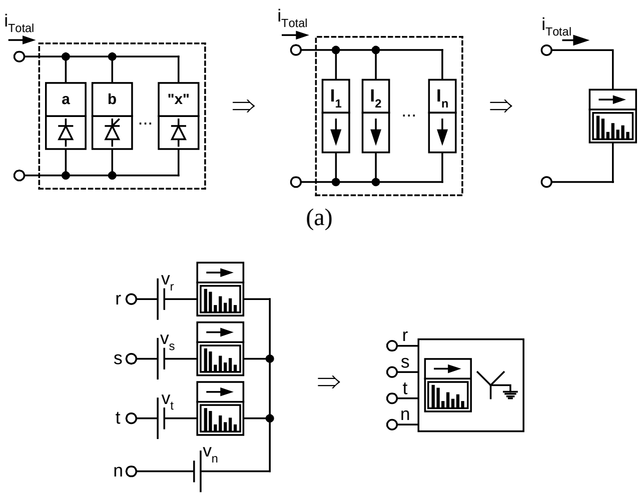


Fig. 3. Model of nonlinear load, based on the Norton approach: (a) single-phase, and (b) three-phase.

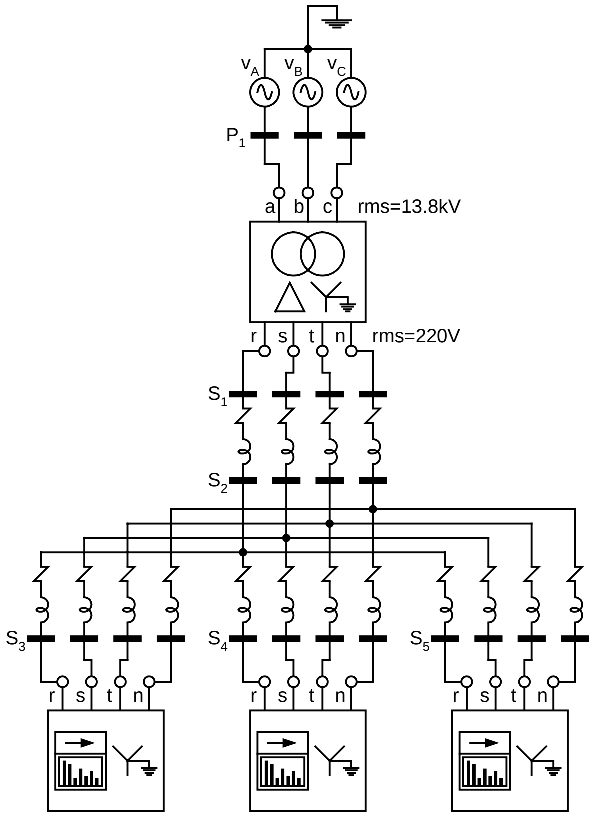


Fig. 4. Simplified schematic diagram of the distribution line simulated in PSpice.

The path between S_1 and S_2 presents two cables for each phase and a single cable for the neutral conductor. The other paths (S_2-S_3, S_2-S_4, and S_2-S_5) present one cable for each phase and one cable for the neutral conductor.

The values of $\overline{r}$ and $\overline{x}$ are provided in datasheets of the cables. Thus, the line's values of R_L and X_L can be obtained according to the distances involved in each path. Finally, the values of L are calculated using (1).

$$L_L = \frac{X_L}{2\pi f} \tag{1}$$

Where:

f = 60Hz (ac system oscillating frequency)

The parameters of the equivalent loads (Table II) are based on experimental measurements performed with a data acquisition system. Each equivalent load will be represented by fifteen current sources, representing each harmonic order presented in Table II.

TABLE I
PARAMETERS OF THE SECONDARY LINE (S_1 UNTIL S_5)

Path		Cable [code]	$\overline{r}$ [mΩ/m]	$\overline{x}$ [mΩ/m]	Distance [m]	R_L [mΩ]	X_L [mΩ]	L_L [μH]
S_1-S_2	phase	70 (x2)	0.3184	0.1096	106	16.875	5.809	15.409
	neutral	50	0.445	0.1127		47.170	11.946	31.688
S_2-S_3	phase	50	0.445	0.1127	24	10.680	2.705	7.175
	neutral	25	0.8891	0.1164		21.338	2.794	7.411
S_2-S_4	phase	50	0.445	0.1127	35	15.575	3.945	10.464
	neutral	25	0.8891	0.1164		31.119	4.074	10.807
S_2-S_5	phase	35	0.6353	0.1128	35	22.236	3.948	10.472
	neutral	25	0.8891	0.1164		31.119	4.074	10.807

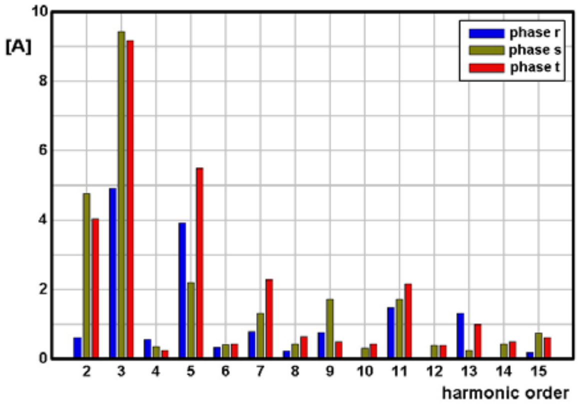
TABLE II
PARAMETERS OF THE NONLINEAR LOADS CONNECTED TO THE SECONDARY LINE

Load Concentration Point	Harmonic Order	Phase r		Phase s		Phase t	
		Amplitude [A]	Phase Angle [º]	Amplitude [A]	Phase Angle [º]	Amplitude [A]	Phase Angle [º]
S_3	1	120.91	-14.6	96.44	-127.9	132.13	121.2
	2	0.60	130.3	4.75	-49.2	4.02	133.6
	3	4.90	171.3	9.43	178.3	9.19	160.3
	4	0.55	100.3	0.34	-95.0	0.23	-21.2
	5	3.91	-163.3	2.20	-28.6	5.49	123.2
	6	0.32	14.0	0.40	-115.6	0.42	99.9
	7	0.78	-131.1	1.30	-24.5	2.27	-172.6
	8	0.21	-65.2	0.43	-110.7	0.64	81.8
	9	0.76	160.0	1.71	-163.8	0.49	159.0
	10	0.02	-103.3	0.31	-85.3	0.42	81.9
	11	1.47	6.3	1.71	126.1	2.15	-160.9
	12	0.01	17.4	0.38	-86.2	0.39	89.3
	13	1.31	-110.0	0.25	-170.7	0.98	88.7
	14	0.06	-91.6	0.43	-80.3	0.48	95.2
	15	0.18	-166.1	0.74	-115.2	0.61	119.6
S_4	1	27.89	-14.0	23.21	-148.4	43.70	96.4
	2	0.13	-118.8	0.04	-75.7	0.36	95.7
	3	6.86	-129.0	3.31	-152.6	6.03	-141.3
	4	0.03	7.6	0.07	-94.0	0.24	108.9
	5	1.77	-156.8	1.24	47.9	2.69	104.8
	6	0.12	-46.4	0.07	-96.6	0.18	91.4
	7	1.80	45.8	1.15	-94.9	1.48	112.3
	8	0.12	-103.3	0.05	-96.5	0.19	82.7
	9	1.69	-64.4	0.63	-87.3	0.98	-7.6
	10	0.06	172.8	0.03	-84.5	0.17	95.9
	11	0.91	164.3	0.49	-107.2	0.42	56.4
	12	0.06	-27.2	0.05	-74.9	0.18	82.9
	13	0.50	82.4	0.22	-54.0	0.16	-88.0
	14	0.11	-98.1	0.05	-77.5	0.19	94.8
	15	0.36	-57.5	0.37	-78.3	0.38	105.0
S_5	1	8.08	-15.3	5.61	-140.2	8.49	103.1
	2	0.09	141.7	0.12	-19.0	0.06	-176.0
	3	2.67	-168.3	0.04	-15.1	2.38	-177.6
	4	0.04	12.3	0.04	-46.5	0.07	155.3
	5	1.49	34.8	0.37	-113.2	1.53	-97.3
	6	0.07	-127.1	0.02	-33.7	0.02	-146.8
	7	0.67	-137.3	0.08	175.6	0.80	-44.5
	8	0.02	66.7	0.04	-61.0	0.03	-5.5
	9	0.17	127.6	0.04	-59.9	0.16	50.2
	10	0.03	-43.1	0.02	-56.8	0.04	77.7
	11	0.38	18.2	0.00	-36.1	0.23	-125.4
	12	0.03	-138.9	0.02	-47.1	0.04	125.2
	13	0.37	-144.9	0.01	-151.3	0.25	-48.0
	14	0.01	102.6	0.01	-59.1	0.01	26.8
	15	0.12	47.1	0.01	0.9	0.17	7.0

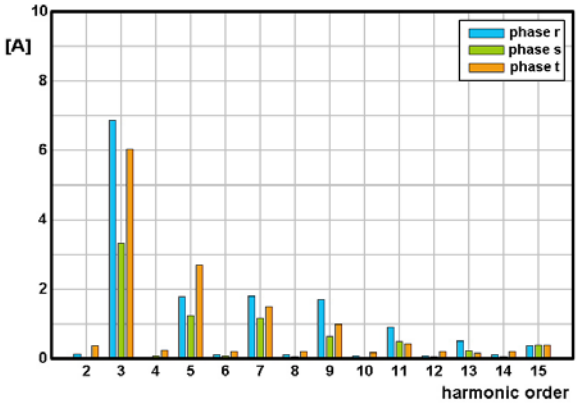
Figure 5 shows the histograms related to the data presented in Table II. The fundamental component was suppressed from these charts, in order to increase the emphasis in the harmonic contents.

According to Table II and Figure 5, it is possible to note that the load connected to the LCP S_3 is the most significant in the system. The presence of significant values of second order harmonics in the currents of phase s and phase t denotes the existence of dc levels in these currents. The LCP S_5 presents the lightest loads of the system.

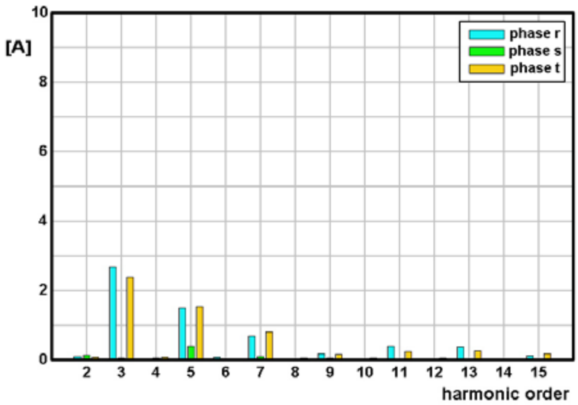
Figure 6 shows the histograms considering the normalization of the data presented in Table II. Each load was normalized according to its own fundamental component.



(a) Phase currents (LCP S_3)



(b) Phase currents (LCP S_4)



(c) Phase currents (LCP S_5)

Fig. 5. Harmonic contents of currents flowing through the distribution line.

Comparing Figures 5 and 6, it is possible to note that the heaviest load (connected to LCP S_3) presents the lowest distortion. Moreover, it is possible to note that the load connected to the LCP S_5 presents the highest distortion, in spite of the low values of currents showed in Table II and Figure 5.

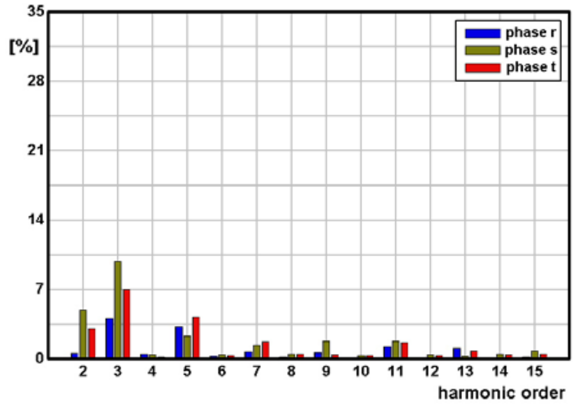
IV. SIMULATION RESULTS

Figure 7 shows the simulation results for the currents drained in the LCPs. This figure depicts the waveforms of the currents processed in the phase and neutral cables. As expected, it is possible to observe that the currents drained in the LCP S_3 present high values, but low harmonic contents.

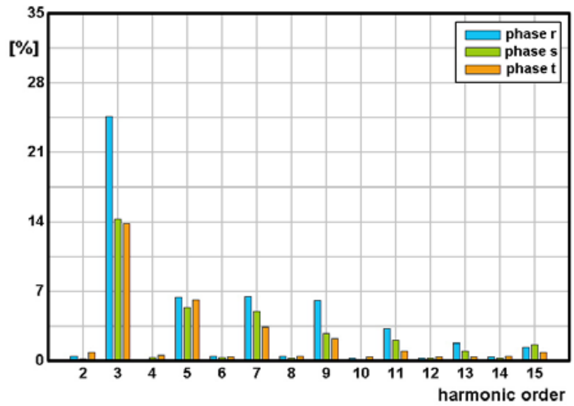
The waveforms of currents flowing through the neutral conductors are also depicted in Figure 7. It can be verified that the load connected to LCP S_4 presents the highest level of rms current flowing through the neutral conductor.

Figure 8 shows the waveforms of the currents that flow from S_1 to S_2, which are the total currents drained in the simulated system. The result showed in Figure 8.b indicates that the neutral current processed in this system is significant, which means that the conduction losses from the neutral conductor cannot be neglected.

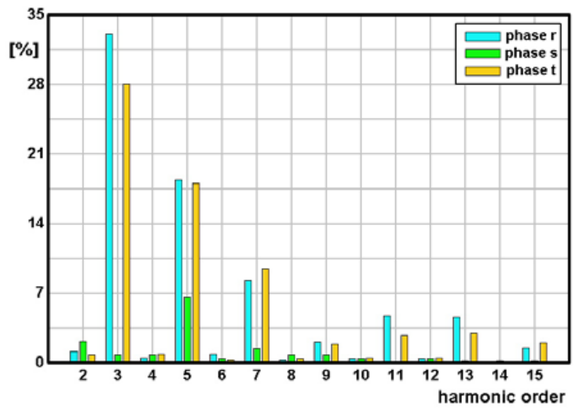
Figure 9 shows the voltage drops along the system, due to the currents processed in each cable. According to this figure, one can conclude that the voltages at the LCPs will be distorted.



(a) Phase currents (LCP S_3)

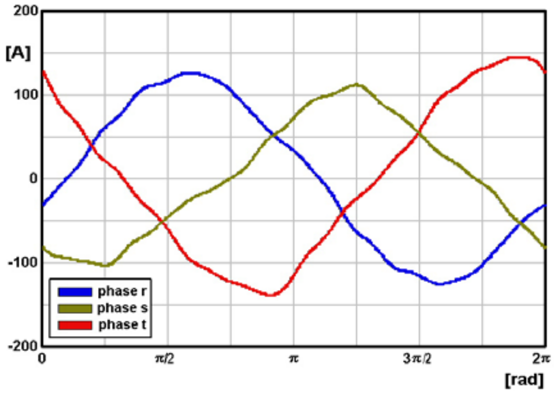


(b) Phase currents (LCP S_4)

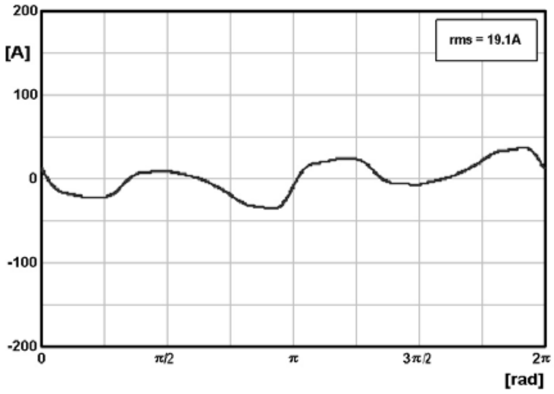


(c) Phase currents (LCP S_5)

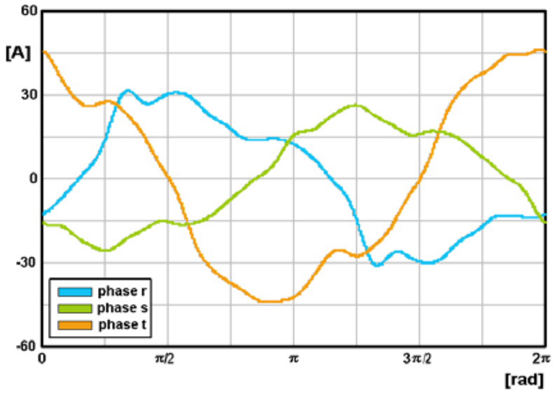
Fig. 6. Normalized harmonic contents of currents flowing through the distribution line.



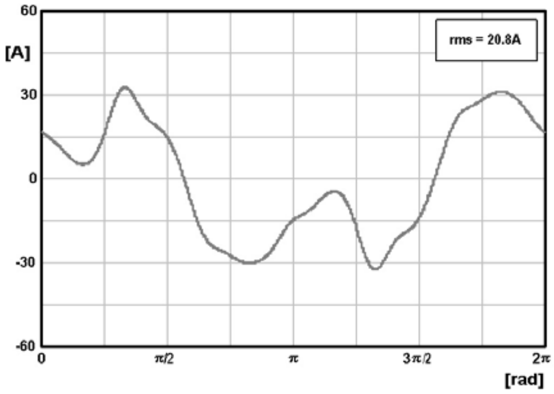
(a) Phase currents (LCP S_3)



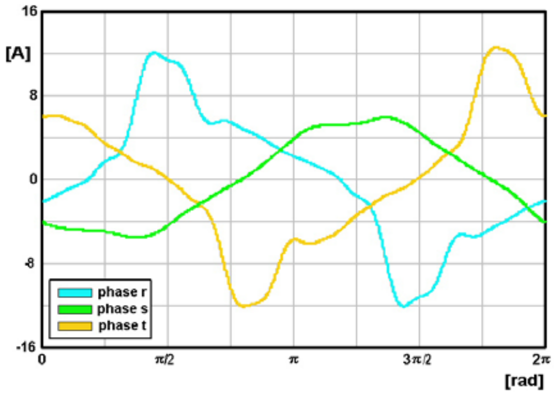
(b) Neutral current (LCP S_3)



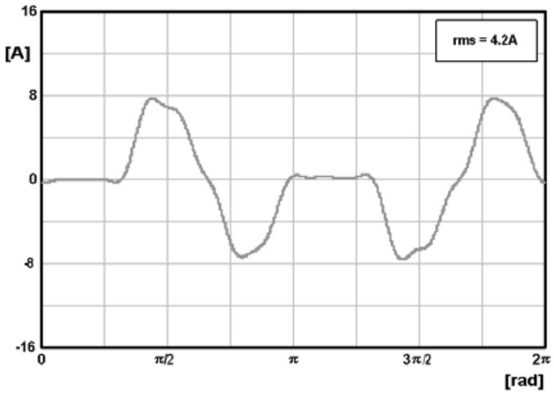
(c) Phase currents (LCP S_4)



(d) Neutral current (LCP S_4)

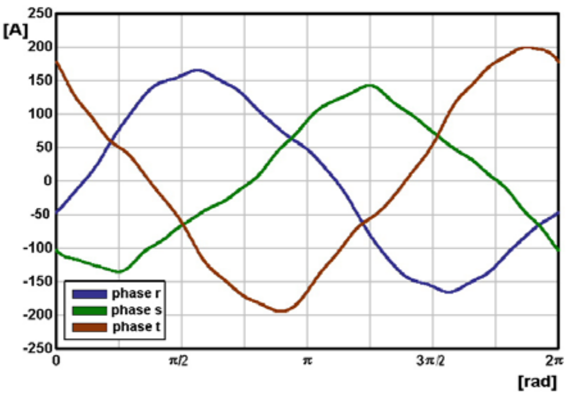


(e) Phase currents (LCP S_5)

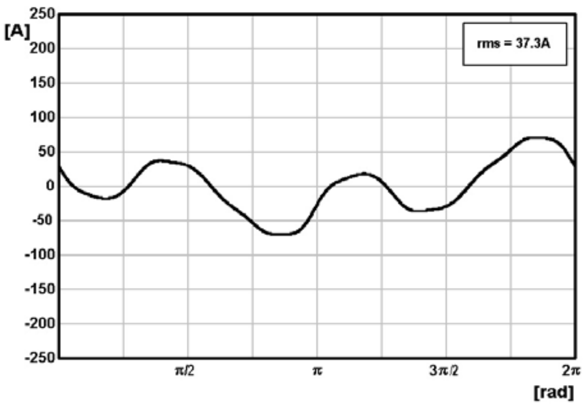


(f) Neutral current (LCP S_5)

Fig. 7. Waveforms of currents drained in the LCPs.

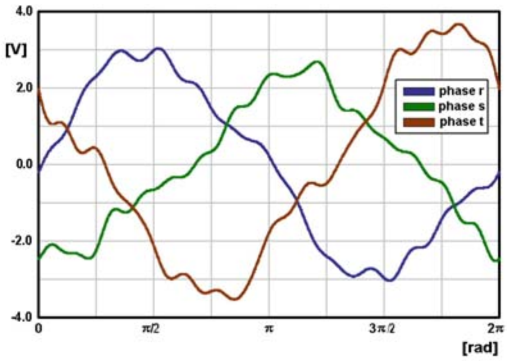


(a) Phase currents (from S_1 to S_2)

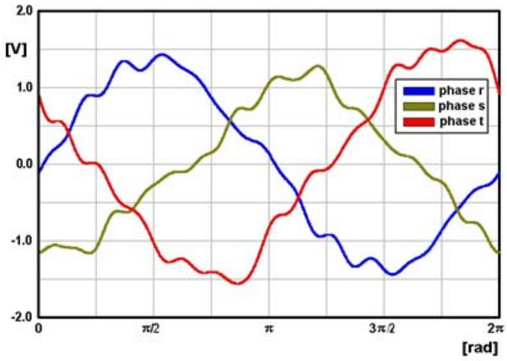


(b) Neutral current (from S_1 to S_2)

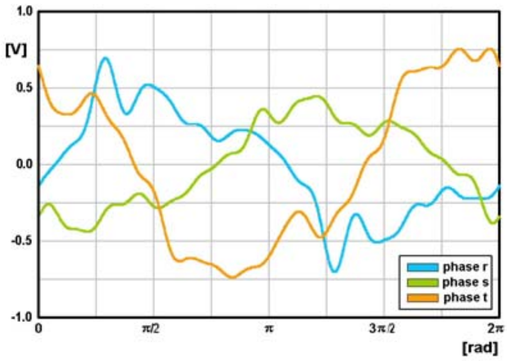
Fig. 8. Waveforms of currents flowing from S_1 to S_2.



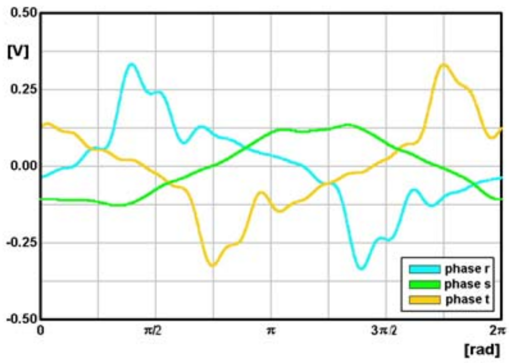
(a) Voltage drops between S_1 and S_2



(b) Voltage drops between S_2 and S_3



(c) Voltage drops between S_2 and S_4



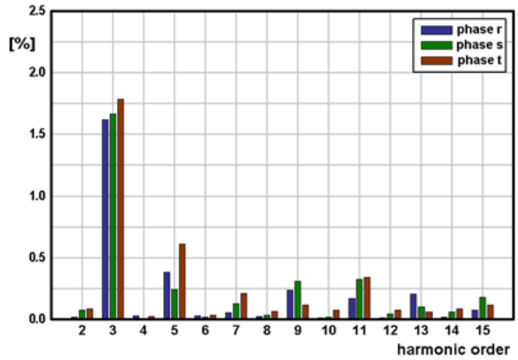
(d) Voltage drops between S_2 and S_5

Fig. 9. Waveforms of voltage drops in the distribution line.

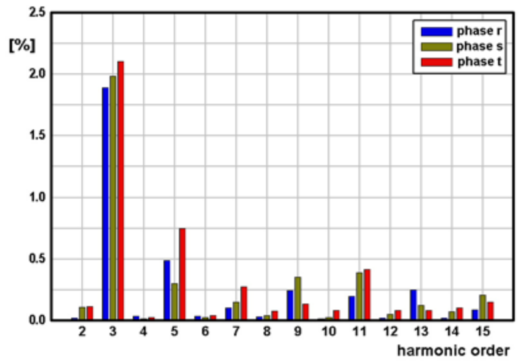
The harmonic contents of the phase voltages at the LCPs are depicted in Figure 10. The values are expressed in percentage, assuming that each fundamental component represents the value of 100%.

As commented before, the supply system (v_A, v_B, and v_C) presents no distortion, because they are ideal voltage sources. Thus, the harmonic contents showed in Figure 10 are directly derived from the presence of nonlinear loads in the system.

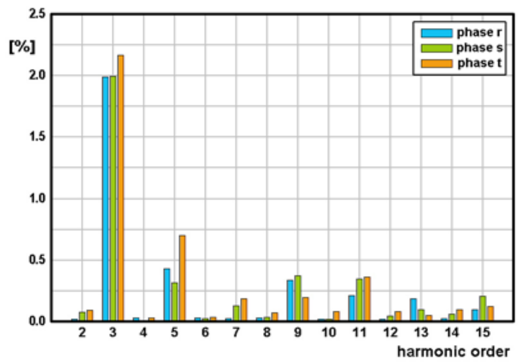
Figure 11 shows the waveforms of the voltage over the neutral point of S_2 and each LCP, considering the neutral point of S_1 as a reference.



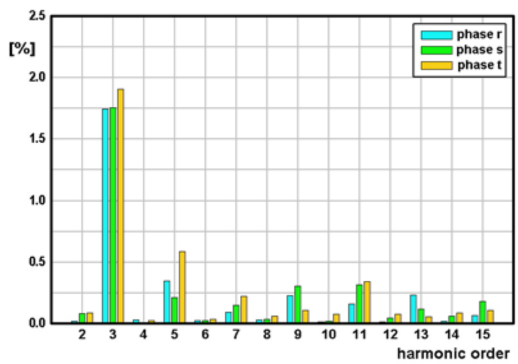
(a) Phase voltages (S_2)



(b) Phase voltages (LCP S_3)

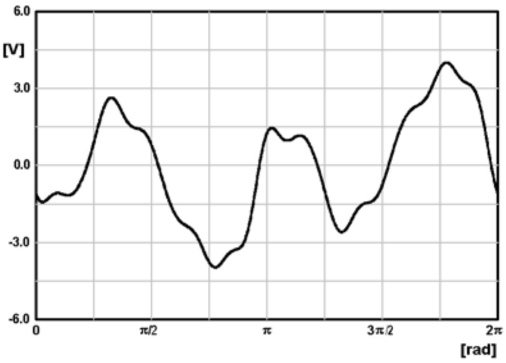


(c) Phase voltages (LCP S_4)

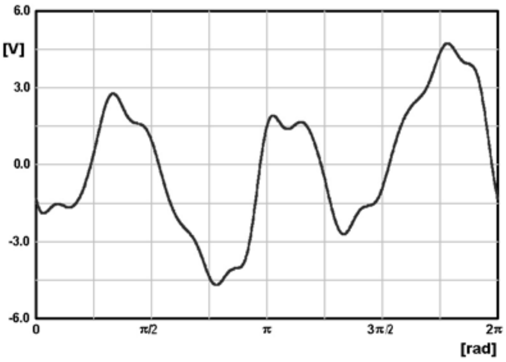


(d) Phase voltages (LCP S_5)

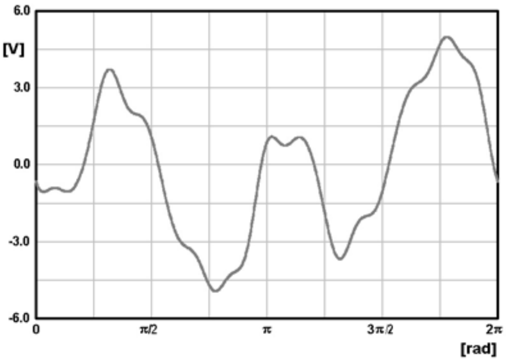
Fig. 10. Harmonic contents of phase voltages in S_2 and in LCPs.



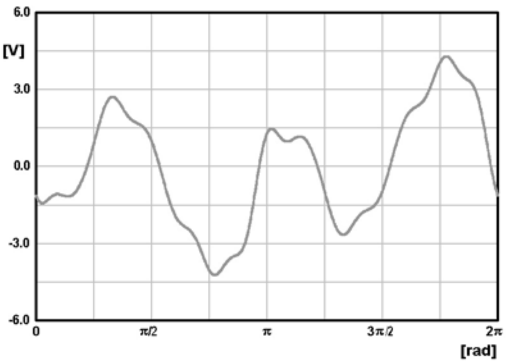
(a) Voltage over the neutral point of LCP S_2



(b) Voltage over the neutral point of LCP S_3



(c) Voltage over the neutral point of LCP S_4



(d) Voltage over the neutral point of LCP S_5

Fig. 11. Waveforms of voltage over the neutral points of S_2 and each LCP, considering the neutral point of S_1 as a reference.

From Figure 11, it can be verified the instantaneous neutral point displacements along the distribution line. These displacements occur due to the presence of significant values of current flowing through the neutral conductors, according to the results showed in Figures 7 and 8.

Figure 12 shows the waveforms of current drained from the supply system (voltage sources v_A, v_B, and v_C). Because of the Δ/Y-grounded connection adopted in the transformer model, it is expected that the currents in the primary present low amount of triplens (third order harmonic and its multiples), reducing the Total Harmonic Distortion when compared to the currents in the secondary.

In order to provide conditions for the verification of this fact, Figure 13 shows the harmonic contents of the primary and secondary currents, processed in the transformer. According to this figure, it is possible to visualize the large

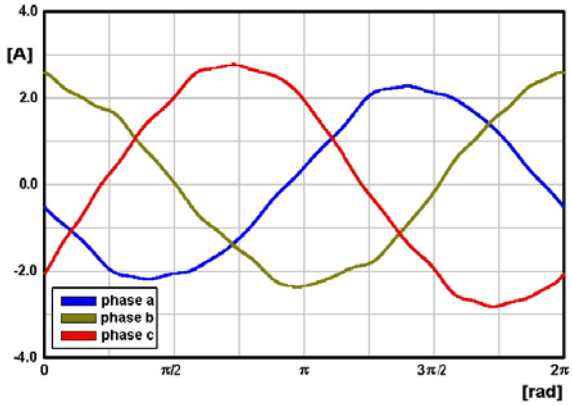
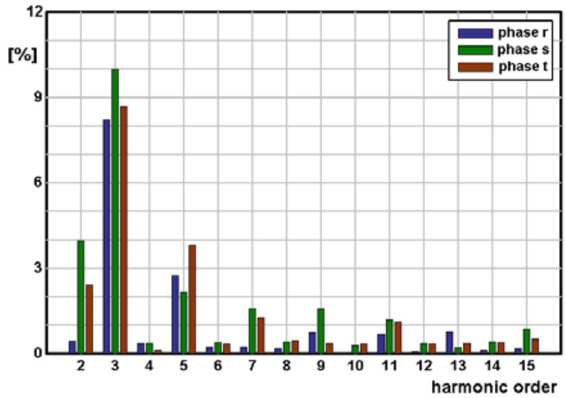
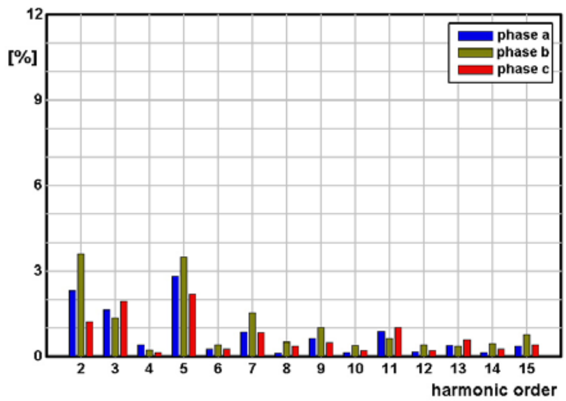


Fig. 12. (a) Waveforms of phase currents drained from the voltage sources v_A, v_B, and v_C.



(a) Phase currents (from the transformer model to S_1)



(b) Phase currents (from P_1 to the transformer model)

Fig. 13. Harmonic contents of line currents processed in the transformer model.

reduction in the third order harmonics, in compliance with the expected behavior of the Δ/Y-grounded connection implemented for the transformer model.

V. CONCLUSIONS

This paper presented a proposal for the simulation and analysis of harmonic contents in voltage and currents of three-phase distribution lines, considering their multifilar representation. In this representation, it is possible to investigate the effects of unbalanced loads connected to the system. Therefore, one of the major drawbacks from the unifilar representation is overcome: the analysis of only balanced systems.

The transformer model employed in the simulation permits the development of proper analyses about the propagation of harmonic contents in the currents and voltages processed in the distribution lines, including the primary line.

So, this proposal has the potential to be very useful and efficient in the evaluation of the expansion of distribution lines and the effects of the growth in the consumption of electrical energy in existing systems, considering the connection of unbalanced nonlinear loads.

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