HARMONIC DISTORTIONS CAUSED BY RADIO AND TELEVISION BROADCASTING STATIONS ON SECONDARY DISTRIBUTION SYSTEMS

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Abstract - **This paper contains a study of the effects of television and radio repeater station broadcasts on electrical power signal behavior. This research topic is relevant because radio and television stations have non-linear loads. The measurement procedures described here and results obtained herewith allow one to obtain important power quality parameters.**

KEYWORDS

Harmonics; power factor; power quality.

I. INTRODUCTION

Brazilian metropolitan areas, and major regional population centers tend to host TV and radio broadcast/repeater stations, which have non-linear loads. These loads give rise to current and voltage power signal distortions, which may compromise the power quality of the electricity supplied to the other consumers on the same distribution branch. Note that such branch sharing, i.e., residential and commercial consumers and TV/radio stations, is a quite common scenario.

In light of these facts, we undertook a study of the electrical behavior of the non-linear loads used by radio and TV broadcasting stations

Two case studies were used in our research. In Case I, the consumer is a TV repeater station, linked to a single-phase feeder branch. In Case II, the consumer is a television repeater station fed by a three-phase branch. These case scenarios allow us to evaluate, both qualitatively and quantitatively, the electrical power quality. In the next section, we present the basic theory necessary for such analysis.

II. THEORETICAL FUNDAMENTALS

Our work adopts the principle that one should use the variables that are actually available at the load terminals. We started with the instantaneous values of current and voltage obtained simultaneously with a power analyzer. These signals are then processed using both numerical analysis theory and expressions that are presented below. Proceeding in this manner, we derive further variables with a good precision.

For starters, a discussion of both the single-phase and the three-phase loads.

SINGLE-PHASE LOAD

We begin with the expressions associated with the time-varying current and voltage signals i(t) and v(t). Supposing a distorted signal we have [3, 5, 7]:

$$v(t) = V_o + \sqrt{2}\sum_{\nu=1}^{\infty} V_\nu \mathrm{sen}(\nu\omega\, t + \alpha_\nu) \quad (1)$$

$$i(t) = I_o + \sqrt{2}\sum_{\nu=1}^{\infty} I_\nu \mathrm{sen}(\nu\omega\, t + \beta_\nu) \quad (2)$$

Where: $\omega = 2\pi f$ (f = 60 Hz for the Brazilian Electrical Power System);
And where:
V_o , I_o – respectively, the continuous voltage and current components;
ν – harmonic order;
V_ν , I_ν – effective values of voltage and current, associated with the harmonics of order ν;
f – fundamental component frequency;
t – time;
α_ν , β_ν – phase angles of, respectively, the voltage and current harmonics of order ν.

The effective values of voltage (V) and current (I) may be obtained from (3) e (4) [1,4,6]:

$$V = \left[\sum_{\nu=0}^{\infty} V_\nu^2\right]^{1/2} \quad (3)$$

$$I = \left[\sum_{\nu=0}^{\infty} I_\nu^2\right]^{1/2} \quad (4)$$

Squaring both sides of equations (3) and (4) and rewriting, one may obtain equations (5) e (6):

$$V^2 = \sum_{\nu=0}^{\infty} V_\nu^2 = V_1^2 + V_N^2 \quad (5)$$

$$I^2 = \sum_{\nu=0}^{\infty} I_\nu^2 = I_1^2 + I_N^2 \quad (6)$$

Where: $V_N^2 = \sum_{\nu \neq 1}^{\infty} V_\nu^2$ e $I_N^2 = \sum_{\nu \neq 1}^{\infty} V_\nu^2$

And where:

V_1, I_1 – effective values of the fundamental components of voltage and current;

Taking expressions (5) and (6) and noting that the square of the apparent power (S) can be written as $S^2 = V^2 I^2$, we have that:

$$S^2 = V_1^2 I_1^2 + V_1^2 I_N^2 + V_N^2 I_1^2 + V_N^2 I_N^2 \qquad (7)$$

Expression (7) may be reformulated as the sum of two terms, as shown in (8):

$$S^2 = S_1^2 + S_N^2 \qquad (8)$$

where:

$S_1^2 = V_1^2 I_1^2$ e $S_N^2 = V_1^2 I_N^2 + V_N^2 I_1^2 + V_N^2 I_N^2$

and where:

S_1 – fundamental apparent power component;

S_N – non-fundamental apparent power component.

The first term of the second part of the non-fundamental apparent power component is, according to [1], known as the current distortion power, while the second term is called the voltage distortion power. The third term is known as the harmonic apparent power.

The fundamental component of the apparent power may be written as:

$$S_1 = \left[P_1^2 + Q_1^2\right]^{1/2} \qquad (9)$$

where:

P_1, Q_1 – fundamental components of the active and reactive power, respectively.

The total harmonic distortion of the voltage (THD_V) and current (THD_I) are given by expressions (10) e (11) [10].

$$THD_V = \left[\frac{V_N^2}{V_1^2}\right]^{1/2} x100(\%) \qquad (10)$$

$$THD_I = \left[\frac{I_N^2}{I_1^2}\right]^{1/2} x100(\%) \qquad (11)$$

Note that:

$$P = \sum_{\nu=1}^{\infty} V_\nu I_\nu cos(\theta_\nu) \qquad (12)$$

where:

θ_ν – difference between the phase angles of the voltage and current signals, i.e., $\theta_\nu = \alpha_\nu - \beta_\nu$.

The power factor (PF) is given by expression (13).

$$PF = \frac{P}{S} \qquad (13)$$

The displacement power factor is given by expression (14) [1,9].

$$dPF = \frac{P_1}{S_1} = \cos\theta_1 \qquad (14)$$

THREE-PHASE LOAD

In Case II, the system load type and configuration may be considered as a three-phase system with harmonics using four unbalanced conductors. In such a scenario, we have that, for a given phase k = (a, b, c), the instantaneous voltage v_k (t) and the current i_k (t) may be given by [2]:

$$v_k(t) = \sqrt{2}\sum_\nu V_{k\nu} sen(\omega_\nu t + \alpha_{k\nu}) \qquad (15)$$

$$i_k(t) = \sqrt{2}\sum_\nu I_{k\nu} sen(\omega_\nu t + \beta_{k\nu}) \qquad (16)$$

where: $\omega_\nu = \nu\omega$;

$V_{k\nu}$, $I_{k\nu}$ – are the effective values of the ν-th voltage and current harmonics, respectively, associated with the given phase k;

ν - is the order of the harmonic;

$\alpha_{k\nu}$, $\beta_{k\nu}$ - are the phase angles of the ν-th voltage and current harmonics, respectively, of the given phase k.

According to [2,8], one may transform the voltage and current phasors of the multiple harmonic orders into symmetric components. In this manner, one may obtain the positive-sequence components, indicated by the upper index +, the negative-sequence components, indicated by the upper index – and the zero-sequence, given by the upper index º. For the current, and considering the ν-th harmonic, one has:

$$\begin{bmatrix} \dot{I}_\nu^0 \\ \dot{I}_\nu^+ \\ \dot{I}_\nu^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} \dot{I}_{a\nu} \\ \dot{I}_{b\nu} \\ \dot{I}_{c\nu} \end{bmatrix} \qquad (17)$$

where: $a = e^{j2\pi/3}$

$\dot{I}_\nu^0$, $\dot{I}_\nu^-$ e $\dot{I}_\nu^+$ - are the zero, negative and positive sequence current components, respectively, associated with the ν-th harmonic;

$\dot{I}_{a\nu}$, $\dot{I}_{b\nu}$ e $\dot{I}_{c\nu}$ - are, respectively, the a, b and c phase line current phasors associated with the ν-th harmonic.

The phase voltages associated with the ν-th harmonic may be processed in a similar fashion, resulting in the positive sequence components $\left(\dot{V}_\nu^+\right)$, the negative sequence components $\left(\overset{\bullet}{V}{}_{\nu}^{-}\right)$ and the zero sequence components $\left(\overset{\bullet}{V}{}_{\nu}^{0}\right)$. These sequence components may be expressed as:

$$\left.\begin{aligned}\overset{\bullet}{V}{}_{\nu}^{+} &= V_{\nu}^{+}\angle\alpha_{\nu}^{+}, \overset{\bullet}{I}{}_{\nu}^{+} = I_{\nu}^{+}\angle\beta_{\nu}^{+}\\ \overset{\bullet}{V}{}_{\nu}^{-} &= V_{\nu}^{-}\angle\alpha_{\nu}^{-}, \overset{\bullet}{I}{}_{\nu}^{-} = I_{\nu}^{-}\angle\beta_{\nu}^{-}\\ \overset{\bullet}{V}{}_{\nu}^{0} &= V_{\nu}^{0}\angle\alpha_{\nu}^{0}, \overset{\bullet}{I}{}_{\nu}^{0} = I_{\nu}^{0}\angle\beta_{\nu}^{0}\end{aligned}\right\} \tag{18}$$

In this fashion, the relevant variables associated with the positive sequence fundamental component, such as the three-phase power $\left(S_1^+\right)$ and the power factor $\left(FP_1^+\right)$ can be obtained from the following expressions:

$$S_1^+ = 3V_1^+ I_1^+ \tag{19}$$

$$P_1^+ = 3V_1^+ I_1^+ \cos\left(\theta_1^+\right) \tag{20}$$

$$Q_1^+ = 3V_1^+ I_1^+ \sin\left(\theta_1^+\right) \tag{21}$$

$$PF_1^+ = \frac{P_1^+}{S_1^+} \tag{22}$$

where: $\theta_1^+ = \alpha_1^+ - \beta_1^+$

According to [6], one may find the effective values of the equivalent voltage (V_e), as well as of the equivalent current (I_e) using expressions (23) e (24):

$$V_e = \left\{\frac{1}{18}\sum_{\nu}\left[3A_{\nu} + B_{\nu}\right]\right\}^{1/2} \tag{23}$$

$$I_e = \left[\sum_{\nu} C_{\nu}/3\right]^{1/2} \tag{24}$$

where:

$$A_{\nu} = V_{a\nu}^2 + V_{b\nu}^2 + V_{c\nu}^2 \tag{25}$$

$$B_{\nu} = V_{ab\nu}^2 + V_{bc\nu}^2 + V_{ca\nu}^2 \tag{26}$$

$$C_{\nu} = I_{a\nu}^2 + I_{b\nu}^2 + I_{c\nu}^2 + I_{n\nu}^2 \tag{27}$$

and furthermore where:

$V_{ab\nu}, V_{bc\nu}$ e $V_{ca\nu}$ - are the effective values of the line voltages associated with the ν-th harmonic;

$I_{ab\nu}, I_{bc\nu}, I_{ca\nu}$ e $I_{n\nu}$ - are the effective values of, respectively, the a, b, c phases and neutral line currents associated with the ν-th harmonic.

Expression (23) may be divided into two portions. The first one corresponds to the fundamental component, known as the equivalent fundamental voltage (V_{e1}) and is given by:

$$V_{e1} = \left\{\frac{1}{18}\left[3A_1 + B_1\right]\right\}^{1/2} \tag{28}$$

In the same manner, the remaining portion, known as the equivalent harmonic voltage (V_{eH}), is given as:

$$V_{eH} = \left\{\frac{1}{18}\sum_{\nu\neq 1}\left[3A_{\nu} + B_{\nu}\right]\right\}^{1/2} \tag{29}$$

Substitution of (28) and (29) into (23) results in:

$$V_e = \left(V_{e1}^2 + V_{eH}^2\right)^{1/2}$$

Applying the same procedure to the current, one may obtain the effective value of the equivalent current as:

$$I_e = \left(I_{e1}^2 + I_{eH}^2\right)^{1/2} \tag{30}$$

where:

$I_{e1} = \left[C_1/3\right]^{1/2}$, $I_{eH} = \frac{1}{3}\sum_{\nu\neq 1} C_{\nu}$

and where:

I_{e1} - is the effective value of the fundamental equivalent current;

I_{eH} - is the effective value of the equivalent harmonic current.

The apparent three-phase equivalent power (S_e) is given by:

$$S_e = 3V_e I_e \tag{31}$$

One may further rewrite the apparent power as:

$$S_e^2 = S_{e1}^2 + S_{eN}^2 \tag{32}$$

where:

$$S_{e1} = 3V_{e1}I_{e1} \tag{33}$$

$$S_{eN}^2 = D_{eI}^2 + D_{eV}^2 + S_{eH}^2 \tag{34}$$

and where:

$D_{eI} = 3V_{e1}I_{eH}$ - is the three-phase power associated with the current distortion;

$D_{eV} = 3V_{eH}I_{e1}$ - is the three-phase power associated with the voltage distortion;

$S_{eH} = 3V_{eH}I_{eH}$ - is the apparent harmonic three-phase power.

The active three-phase power may be obtained with the following expression:

$$P = \sum_{\nu}\left(\sum_{k=a,b,c} V_{k\nu} I_{k\nu}\cos(\theta_{k\nu})\right) \tag{35}$$

where: $\theta_{k\nu} = \alpha_{k\nu} - \beta_{k\nu}$

and where:

$\theta_{k\nu}$ - difference between the voltage and current phase angles;

$\alpha_{k\nu}$, $\beta_{k\nu}$ - are the phase angles of the ν-th harmonics of, respectively, the voltage and current of the given phase k.

Expression (34) may be rewritten as:

$$P = P_1 + P_H \quad (36)$$

where:

P_1 - fundamental three-phase active power given by:

$$P_1 = \sum_{k=a,b,c} V_{k1} I_{k1} \cos(\theta_{k1}) \quad (37)$$

P_H - harmonic three-phase active power given by:

$$P_H = \sum_{\nu \neq 1} \left(\sum_{k=a,b,c} V_{k\nu} I_{k\nu} \cos(\theta_{k\nu}) \right) \quad (38)$$

From (34) and (38) one may obtain the non-active non-fundamental equivalent three-phase power as being expression (39):

$$N_e = \left(S_{eN}^2 - P_H^2\right)^{1/2} \quad (39)$$

From expressions (19) e (33) one may obtain the imbalance factor (GD), an important variable in this case study, from the expression:

$$GD = \frac{\left[S_{e1}^2 - \left(S_1^+\right)^2\right]^{1/2}}{S_{e1}} \quad (40)$$

The equivalent three-phase power factor (PFe), and the total harmonic voltage (THD_{eV}) and current (THD_{eI}) distortions may be obtained from the expressions below:

$$PF_e = \frac{P}{S_e} \quad (41)$$

$$THD_{eV} = \frac{V_{eH}}{V_1}, \; THD_{eI} = \frac{I_{eH}}{I_1} \quad (42)$$

III. CASE STUDIES

Two case studies were undertaken, based on measurements taken from two consumers supplied by 13.8 kV primary branches with transformer stations. These two consumers are: a TV repeater station (Case I) and a radio broadcast station (Case II).

The measurements were taken with the Power Platform® PP-4300 digital power analyzer from Dranetz BMI.

A computer program was developed to process the measured signals. The program uses numerical analysis theory and the theory presented above, in section 2. This procedure results in a good precision.

CASE I

In this scenario, as mentioned previously, the consumer is a TV signal repeater station, with a 220 V single-phase secondary feeder, represented by the unifilar diagram in figure 1.

Four different load conditions were analyzed. The first (situation 1) corresponds to a situation in which all loads are on-line. In situation 2 only the UHF transmitter is turned off. In situation 3, only the VHF transmitter is turned off. And finally, all loads are off-line in situation 4. The graphs in figures 2 and 3 show the voltage and current waveforms, respectively, for situation 1.

The Table I contains the measured signals for each situation.

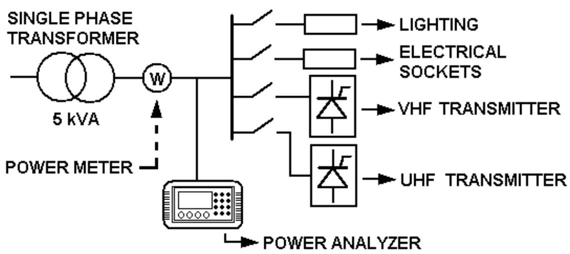

FIGURE 1 - Unifilar diagram of the TV repeater station.

TABLE I
TV repeater station measurements.

	Situation			
Variable	**1**	**2**	**3**	**4**
V_{rms} (V)	220.35	218.49	217.78	217.02
I_{rms} (A)	4.69	1.69	0.86	-
THD_V (%)	7.24	7.03	6.77	6.26
THD_I (%)	34.19	105.75	82.35	-
P_1 (W)	800.00	235.66	123.48	-
Q_1 (var)	556.86	91.80	74.21	-
P (W)	811.65	248.11	128.19	-
S_1 (VA)	974.72	252.91	144.06	-
S_N (VA)	341.45	268.63	119.27	-
S (VA)	1032.80	368.95	187.02	-
PF	0.82	0.93	0.86	-

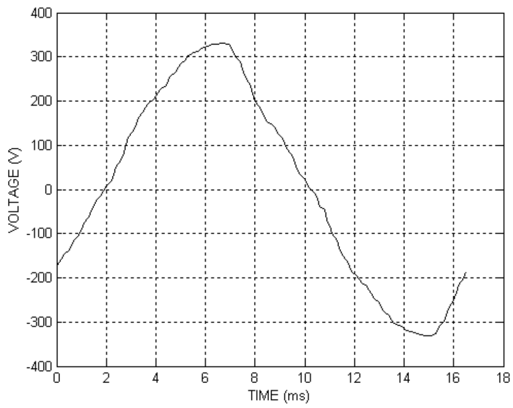

FIGURE 2 - Time-variant voltage waveform (situation 1).

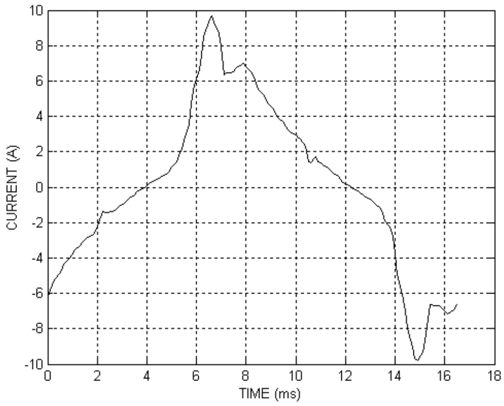

FIGURE 3 - Time-variant current waveform (situation 1).

CASE II

This case concerns an FM radio broadcast station fed by a 380 V secondary voltage (line voltage). A voltage regulator is used to lower the voltage from 380 V to 220 V. Figure 4 shows a unifilar diagram of the situation described above.

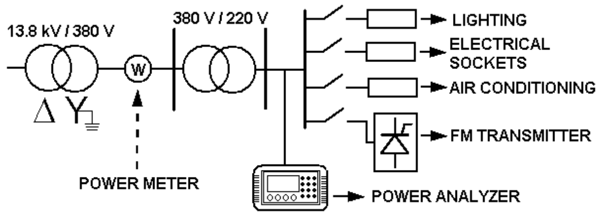

FIGURE 4 - Unifilar diagram of the FM radio broadcast station.

As was done in Case I, we analyzed four different scenarios:

1- All loads on-line;
2- Only the air conditioner off-line;
3- Only the FM transmitter turned off;
4- All loads off-line.

The voltage and current waveforms for the full load situation are given in figures 5 and 6.

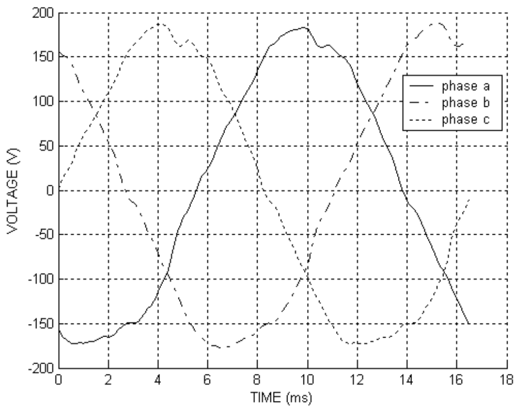

FIGURE 5 - FM Radio broadcast station feeder voltage waveform.

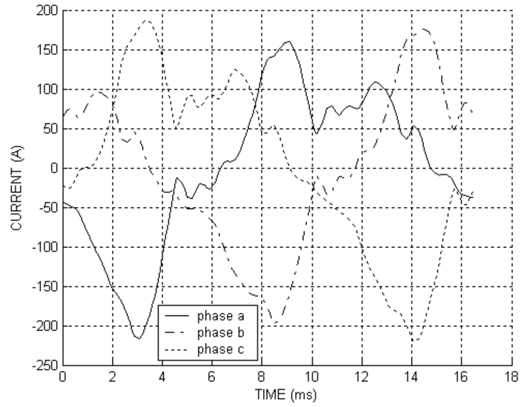

FIGURE 6 - FM radio broadcast station feeder current waveform.

To better visualize the harmonic levels, the harmonic spectra associated with phase a of the signals in figures 5 and 6, are shown, respectively, in figures 7 and 8.

Note the presence of even-order harmonics, caused by the waveforms asymmetry relative to the positive and negative semi-cycles.

The results obtained with the measurements taken at the radio broadcaster are given in Table II.

TABLE II
Results obtained with the measurements taken at the radio broadcast station.

	Scenarios			
Variable	1	2	3	4
Va_{rms} (V)	125.39	124.67	126.93	126.76
Vb_{rms} (V)	126.38	125.86	127.95	3.12
Vc_{rms} (V)	126.34	125.82	128.08	3.33
Ia_{rms} (A)	96.50	96.79	6.39	-
Ib_{rms} (A)	98.75	86.38	6.83	-
Ic_{rms} (A)	107.55	95.01	8.27	-
THD_{Va} (%)	4.85	4.44	3.37	3.27
THD_{Vb} (%)	4.57	4.35	3.21	3.12
THD_{Vc} (%)	4.91	4.57	3.45	3.33
THD_{Ia} (%)	45.23	46.97	73.47	-
THD_{Ib} (%)	41.20	51.72	55.46	-
THD_{Ic} (%)	40.13	49.03	53.88	-
P_1+ (W)	33946.00	30379.00	1479.40	-
$P_{\xi 1}$ (W)	13.29	1.20	1.82	-
Q_1+ (var)	8857.00	7273.20	1790.30	-
$Q_{\xi 1}$ (var)	3.64	13.89	2.13	-
P_N (W)	129.58	119.20	2.40	-
Q_N (var)	536.81	530.17	41.64	-
P (W)	34002.00	30384.00	1484.50	-
S (VA)	35087.00	31242.00	2322.80	-
PF	0.97	0.97	0.64	

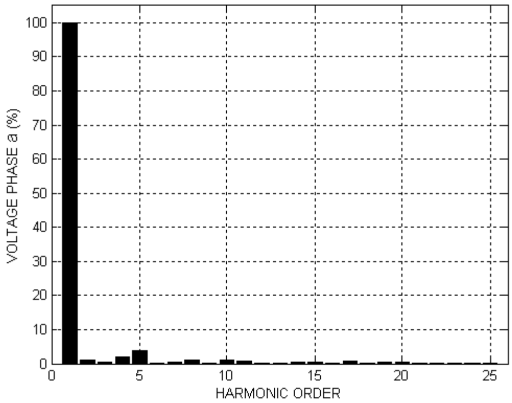

FIGURE 7 - Harmonic spectrum of phase a of the voltage waveform shown in figure 5.

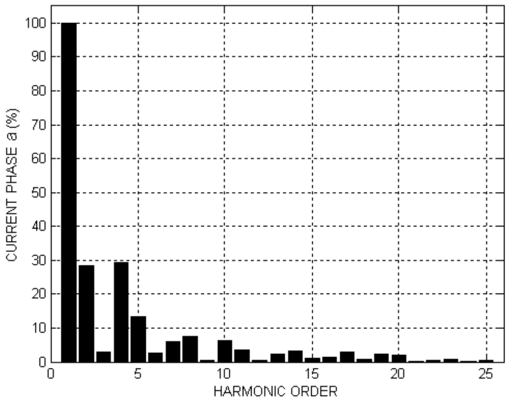

FIGURE 8 - Harmonic spectrum of phase a of the current waveform shown in figure 7.

IV. CONCLUSIONS

In this paper we analyzed the behavior of some relevant variables associated with power quality, considering the presence of feeder-branch harmonics, under two representative load scenarios.

It is reasonable to describe the load cases investigated, given the presented results and graphs, as non-linear.

The TV repeater station presented a high level of total harmonic distortion, even in the voltage signal, where it surpassed 7% at full load, as well as presenting a low power factor. In the same fashion, the radio broadcast station presented considerable distortion in the electrical signals observed at its power terminals.

It is of note that in case II the power factor (PFe) value is very close to that associated with the fundamental components of the positive sequence.

The marked distortion in the observed voltage and current signals may compromise the power quality of the remaining consumer sharing the same distribution branch. In such cases, a solution can be found with the use of filters, which is precisely the subject of our continued investigations.

REFERENCES

[1] Arseneau. R. et. al. IEEE Working Group on Nonsinusoidal Situations: Effects on Meter Performance and Definitions of Power. “Practical Definitions for Powers in Systems with Nonsinusoidal Waveforms and Unbalanced Loads: A Discussion”. IEEE Transactions on Power Delivery. Vol. 11. USA. 79-87, 1996.

[2] Watanabe. Edson H.; Aredes. Maurício. “Teoria de Potência Ativa e Reativa Instantânea e Aplicações”. Proc. of the XII Congresso Bras. de Automática. Uberlândia. MG. pp. 81-122, 1998.

[3] Strum. Robert D.;Ward. John R.. A. Electric Circuits and Networks. 2. Ed. Prentice-Hall. Inc.. Englewood Cliffs. New Jersey, 1985.

[4] Dugan. R. C.; McGranaghan. M. F. ; Beaty. H. W. Electrical Power Systems Quality. McGraw-Hill. USA, 1995.

[5] Strum. Robert D.; Kirk. Donald E. First Principles of Discrete Systems and Digital Signal Processing. Addison - Wesley. USA, 1993.

[6] Emanuel. A. E. “Apparent Power Definitions For Three-Phase Systems”. IEEE Transactions on Power Delivery, 1998.

[7] Arrilaga. J.; Bradley. D. A.; Bodger. P. S. Power Systems Harmonics. J. Wiley. New York, 1985.

[8] Stevenson Jr.. William. Elements of power system analysis. 4. Ed. McGraw-Hill Book Company. USA, 1982.

[9] Dias, Guilherme A. Dontizien. Harmônicas em Sistemas Industriais. EDIPUCRS. Porto Alegre, 1998.

[10] Rashid. Muhammad H. Power Electronics Circuits. Device. and Applications. 2. Ed. Prentice Hall International Edition, 1993.