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ESTIMATION OF SINGLE-PHASE UNCONTROLLED RECTIFIER PARAMETERS

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ABSTRACT
In this paper, single-phase uncontrolled rectifier parameters are estimated from actual measurements using rectifier invariants and a harmonic current database, which characterize the harmonic currents consumed by these devices. Measurements in a personal computer (PC) and a television (TV) are made to study the use of the database.

KEY WORDS
Single-phase uncontrolled rectifiers, power system harmonics, non-linear devices, parameter estimation

1. Introduction

Harmonic studies are receiving more attention due to the growing number of non-linear loads connected to the distribution system. A set of these loads uses single-phase rectifiers with DC-smoothing capacitors as their power supply. Although these loads currently account for a small percentage of the total load, this percentage is increasing due to their high efficiency. Unfortunately, this results in problematic voltage distortion levels. For this reason, several studies trying to predict the harmonic currents injected by these non-linear loads can be found in the literature. Apart from the magnitude of harmonic currents, some of these studies evaluate their phase angle to determine harmonic current content completely.

Most of the above studies include complicated analytical expressions or graphs based on extensive simulations of the rectifier to calculate the harmonic currents [1-7]. Unfortunately, either their theoretical methods are not experimentally validated or the validation is performed with few experiments [6, 7]. There are only a few studies that analyze rectifier behavior experimentally [8-10]. In [10], single-phase rectifier behavior is experimentally studied assuming sinusoidal supply voltages. Experimental tests are conducted to characterize the absorbed harmonic currents (magnitude and phase angle), and a harmonic current database of rectifiers is obtained from these tests. The harmonics of in database are univocally characterized from the rectifier invariants, which are the minimum number of parameters needed to completely characterize non-linear load behavior [11]. Thus, both the database and the invariants can be used in works concerning single-phase rectifiers as they allow their fundamental and harmonic currents to be calculated in an easy and friendly way.

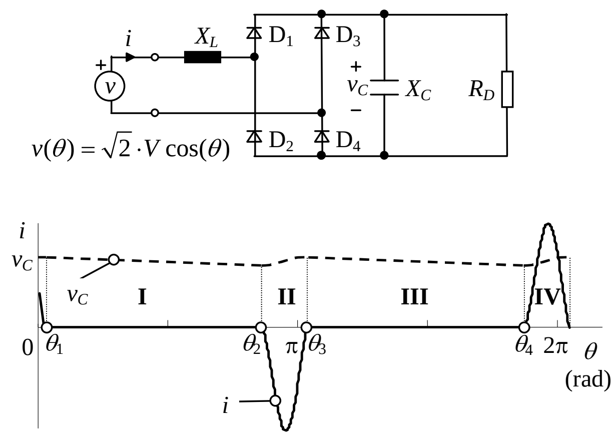

Fig. 1. Equivalent circuit and AC current and DC voltage waveforms of the single-phase rectifiers.

The present paper, estimates single-phase uncontrolled rectifier parameters from actual measurements with the database provided in [10]. Measurements in a personal computer (PC) and a television (TV) are employed to estimate the parameters of these devices using the above database.

2. Single-Phase Rectifier Modelling

The equivalent circuit of the single-phase recitifier, as well as the AC current i and DC voltage v_C of the rectifier, are illustrated in Fig. 1. This plot shows the commutation angles, which define the non-linear load current. The current and voltage characterizing the behavior of this load can be determined by analyzing the circuit topologies of the corresponding circuit, [1, 2, 4, 11]. The considered model of the single-phase recitifier is based on the following hypotheses [5, 11]:

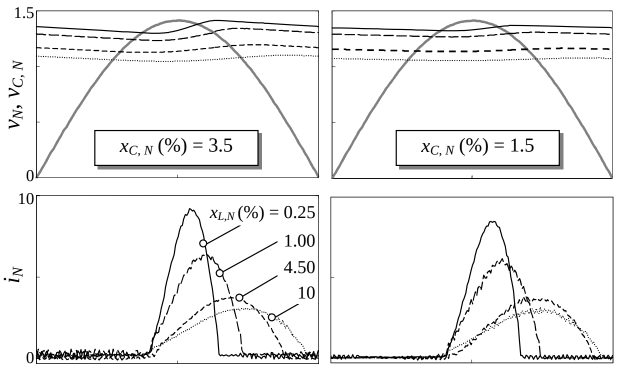

Fig. 2. Invariant influence on the rectifier AC current and DC voltage waveforms.

- The supply voltages are assumed to be sinusoidal, which is reasonable for voltage distortion levels in actual distribution systems (approximately 2 – 3%) [1, 8, 10, 11].
- The resistances of the AC supply system impedances are not considered because their influence on non-linear load behavior is much smaller than that of the inductive reactance [1, 4, 8].
- The resistance R_D models the DC power consumption of the rectifier [1-3, 5].
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As developed in [11] and according to Fig. 1, the equations that characterize the rectifier behavior can be normalized by using the references $U_R = V$, $Z_R = R_D$, and therefore $I_R = U_R / Z_R = V/R_D$. In this way, the behavior of this load, defined by the normalized variables $i_N = i/I_R$ and $v_{C,N} = v_C / U_R$, can be univocally characterized from the following normalized parameters:

$$x_{L,N} = \frac{X_L}{R_D} \quad , \quad x_{C,N} = \frac{X_C}{R_D}. \tag{1}$$

These parameters are called invariants of the rectifier and their usefulness lies in the fact that they are the minimum number of parameters required to completely characterize non-linear load behavior, allowing these loads to be studied in a simple way.

The usual range of $x_{L,N}$ and $x_{C,N}$ values in practical applications was obtained in [11] by relating each one of these invariants to the short-circuit ratio $R_{SC} = S_{CC}/S_{Load}$ and the rectifier DC voltage ripple $\Delta v_C/V_C$, respectively. Thus, the usual values of $x_{L,N}$ and $x_{C,N}$ are $x_{L,N}$ (%) = (0.05 … 10) and $x_{C,N}$ (%) = (0.5 … 4.5), which approximately correspond to a R_{SC} = (5 … 1000) and a $\Delta v_C / V_C$ (%) = (1 … 10), respectively.

Fig. 2 shows the influence of these invariants on the rectifier AC current and DC voltage waveforms. This plot also illustrates the supply voltage waveforms, which were measured in the laboratory for low and high DC voltage ripple according to $x_{C,N}$ = 1.5 and 3.5%, respectively, and

TABLE 1
RMS VALUES OF THE NORMALIZED HARMONIC CURRENTS, $I_{h,N}$ (pu)

$x_{L,N}$ (%)	$I_{1,N}$	$I_{3,N}$	$I_{5,N}$	$I_{7,N}$	$I_{9,N}$	$I_{11,N}$
0.05	1.92	1.82	1.65	1.40	1.12	0.83
0.075	1.91	1.80	1.61	1.34	1.04	0.74
0.1	1.90	1.74	1.53	1.18	0.81	0.50
0.2	1.88	1.68	1.31	0.90	0.52	0.19
0.3	1.86	1.63	1.26	0.82	0.43	0.17
0.4	1.84	1.59	1.14	0.64	0.25	0.13
0.5	1.83	1.55	1.08	0.54	0.23	0.13
0.6	1.82	1.52	1.05	0.56	0.21	0.12
0.7	1.80	1.48	1.00	0.50	0.17	0.13
0.8	1.79	1.45	0.95	0.44	0.15	0.14
0.9	1.77	1.43	0.90	0.40	0.13	0.13
1.0	1.76	1.40	0.85	0.35	0.12	0.12
1.5	1.71	1.29	0.70	0.22	0.13	0.10
2.0	1.67	1.20	0.58	0.17	0.14	0.08
2.5	1.64	1.12	0.45	0.14	0.12	0.06
3.0	1.62	1.07	0.40	0.13	0.11	0.05
3.5	1.59	1.02	0.35	0.12	0.09	0.05
4.0	1.57	0.97	0.30	0.12	0.08	0.05
4.5	1.55	0.93	0.27	0.12	0.07	0.05
5.0	1.53	0.90	0.24	0.13	0.07	0.05
5.5	1.52	0.86	0.21	0.12	0.06	0.05
6.0	1.50	0.83	0.19	0.12	0.05	0.05
6.5	1.49	0.80	0.17	0.12	0.05	0.05
7.0	1.47	0.78	0.16	0.11	0.05	0.04
7.5	1.46	0.75	0.15	0.11	0.05	0.04
8.0	1.45	0.73	0.13	0.10	0.05	0.03
8.5	1.43	0.71	0.13	0.10	0.05	0.03
9.0	1.42	0.68	0.12	0.09	0.05	0.02
9.5	1.41	0.65	0.13	0.10	0.06	0.03
10.0	1.40	0.64	0.11	0.08	0.04	0.02

for four $x_{L,N}$ values. It can be seen that the invariant $x_{L,N}$ mainly influences the shape of the line current pulse (a small invariant $x_{L,N}$ leads to a sharp line current pulse and enlarges the harmonic currents) whereas the invariant $x_{C,N}$ mainly influences the DC voltage ripple (a small invariant $x_{C,N}$ leads to a small ripple) [10, 11].

Finally, according to the Fourier series of the rectifier consumed currents $i(\theta)$, the harmonic currents $\underline{I}_h$ injected by these rectifiers can be easily obtained by multiplying the normalized harmonic currents $\underline{I}_{h,N}$ by the reference current of the load $I_R = U_R/Z_R = V/R_D$:

$$\begin{aligned} \underline{I}_h &= \frac{1}{\sqrt{2}} \frac{1}{\pi} \int_0^{2\pi} i(\theta) e^{-jh\theta} d\theta = \\ &= \frac{1}{\sqrt{2}} \frac{1}{\pi} \int_0^{2\pi} I_R i_N(\theta) e^{-jh\theta} d\theta = I_R \underline{I}_{h,N} \\ &= \frac{V}{R_D} \cdot \underline{g}_h (x_{L,N}, x_{C,N}) \qquad (h = 3, 5, 7 \ldots) \end{aligned} \tag{2}$$

3. Experimental Characterization of the Single-Phase Rectifier Behavior

A database of the rectifier normalized fundamental and harmonic currents, $\underline{I}_{h,N} = I_{h,N} \angle \phi_h$, was experimentally obtained for the above invariant values in [10]. To this end, the rectifier of Fig. 1 was constructed in the laboratory and experimental tests were performed with it.

TABLE 2
PHASE ANGLES OF THE NORMALIZED HARMONIC CURRENTS, ϕ_h (º) FOR $x_{C,N}$ = 1.5 %

$x_{L,N}$ (%)	ϕ_1	ϕ_3	ϕ_5	ϕ_7	ϕ_9	ϕ_{11}
0.05	–4.7	–15.6	–26.2	–37.8	–50.5	–65.5
0.075	–5.4	–17.7	–29.8	–43.0	–57.9	–76.5
0.1	–6.1	–19.7	–33.4	–48.1	–65.3	–87.5
0.2	–8.8	–27.8	–47.6	–69.4	–97.1	–141.0
0.3	–10.0	–32.2	–55.2	–81.9	–118.8	180.0
0.4	–11.4	–35.9	–61.8	–92.3	–140.2	130.8
0.5	–11.8	–37.3	–64.4	–97.1	–153.0	113.6
0.6	–12.2	–38.8	–66.9	–102.0	–165.8	96.4
0.7	–13.0	–41.0	–70.8	–109.0	–180.0	79.3
0.8	–13.9	–43.7	–76.0	–118.3	155.6	62.9
0.9	–14.6	–45.9	–79.9	–126.3	138.3	50.7
1.0	–15.3	–48.0	–83.8	–134.4	121.9	38.5
1.5	–17.8	–56.0	–99.9	–172.0	69.0	–10.1
2.0	–19.7	–62.2	–111.9	150.7	35.6	–52.5
2.5	–21.4	–67.3	–124.0	117.4	3.1	–90.1
3.0	–22.9	–72.1	–134.9	89.6	–1.7	–135.8
3.5	–24.3	–76.7	–145.5	67.8	–34.8	–180.0
4.0	–25.4	–80.7	–155.8	51.5	–52.8	159.8
4.5	–26.4	–83.8	–164.3	39.9	–70.1	140.1
5.0	–27.3	–86.8	–173.2	28.1	–88.7	122.7
5.5	–28.1	–89.8	–180.0	17.1	–109.2	104.6
6.0	–28.9	–92.5	168.7	8.1	–128.0	88.6
6.5	–29.7	–94.9	160.3	–0.2	–142.8	76.5
7.0	–30.4	–97.2	151.8	–7.5	–158.0	65.4
7.5	–31.0	–99.4	143.1	–14.3	–180.0	50.9
8.0	–31.5	–101.3	134.8	–21.0	175.4	35.2
8.5	–32.1	–103.3	127.5	–26.6	162.9	20.9
9.0	–32.8	–105.0	120.4	–31.6	154.3	11.6
9.5	–33.0	–106.5	113.9	–39.8	147.0	–5.6
10.0	–33.4	–108.3	104.7	–46.6	135.8	–23.5

Given the dominant influence of the invariant $x_{L,N}$ on the line current (Fig. 2), five values of $x_{C,N}$ (%) (0.5, 1.5, 2.5, 3.5 and 4.5) and thirty values of $x_{L,N}$ (%) (from 0.05 to 10) were considered. The rectifier was fed by a sinusoidal supply voltage of null phase angle. As an example of the harmonic current database, Table 1 shows the rms values of the normalized harmonic currents $I_{h,N}$ and Tables 2 and 3 show their phase angles ϕ_h for $x_{C,N}$ = 1.5 and 2.5%, respectively. It must be noted that the rms values of the currents do not depend on the invariant $x_{C,N}$ [10, 11].

The above database allows the fundamental and harmonic currents of any single-phase rectifier to be calculated. To accomplish this, the normalized fundamental and harmonic currents of the rectifier are obtained considering the value of the rectifier invariants $x_{L,N}$ and $x_{C,N}$. Next, the rectifier currents are calculated from (2) considering the previously obtained normalized fundamental and harmonic currents, $\underline{I}_{h,N} = I_{h,N}\angle\phi_h$, and the rectifier reference current, $I_R = U_R/Z_R = V/R_D$ (where R_D is the rectifier DC resistance). Note that the supply voltage phase angle was fixed to zero in the experimental tests to obtain the database.

TABLE 3
PHASE ANGLES OF THE NORMALIZED HARMONIC CURRENTS, ϕ_h (º) FOR $x_{C,N}$ = 2.5 %

$x_{L,N}$ (%)	ϕ_1	ϕ_3	ϕ_5	ϕ_7	ϕ_9	ϕ_{11}
0.05	–1.8	–7.0	–11.9	–17.6	–23.7	–32.4
0.075	–2.6	–9.5	–16.3	–23.8	–32.4	–44.4
0.1	–3.8	–12.0	–20.6	–30.0	–41.1	–56.3
0.2	–6.7	–22.0	–37.5	–55.1	–77.1	–113.6
0.3	–8.3	–27.3	–46.9	–69.5	–101.5	–165.2
0.4	–9.2	–29.3	–50.6	–76.2	–118.2	161.8
0.5	–9.5	–31.0	–54.9	–81.3	–132.5	139.3
0.6	–10.9	–34.6	–59.9	–91.4	–149.7	112.8
0.7	–11.7	–36.8	–63.6	–98.4	–180.0	94.3
0.8	–12.6	–39.5	–69.1	–107.5	172.7	77.7
0.9	–13.4	–41.9	–73.5	–115.7	154.5	65.1
1.0	–14.1	–44.3	–77.9	–123.8	136.3	52.5
1.5	–16.8	–52.8	–94.1	–162.1	78.9	3.0
2.0	–18.9	–59.6	–107.3	162.2	45.6	–39.9
2.5	–19.6	–63.9	–115.2	131.1	37.2	–80.4
3.0	–21.2	–68.3	–126.1	100.0	7.4	–125.0
3.5	–23.7	–75.2	–142.4	73.0	–27.9	–165.4
4.0	–25.0	–79.1	–152.0	55.4	–46.3	180.0
4.5	–26.0	–82.3	–161.0	42.4	–63.1	146.1
5.0	–26.9	–85.3	–170.2	31.7	–83.5	127.8
5.5	–27.7	–88.3	–180.0	21.8	–103.2	110.5
6.0	–28.6	–91.1	177.4	16.8	–120.9	100.5
6.5	–29.3	–93.6	170.3	8.4	–137.2	88.7
7.0	–29.9	–95.7	155.8	–3.9	–150.6	68.5
7.5	–30.6	–97.8	147.6	–10.9	–165.0	52.6
8.0	–31.2	–100.1	138.5	–16.5	–180.0	42.1
8.5	–31.6	–101.9	131.7	–25.2	168.9	29.7
9.0	–32.3	–103.7	124.3	–31.3	159.8	13.1
9.5	–32.6	–105.5	114.5	–38.3	150.2	2.4
10.0	–33.0	–107.2	108.5	–45.1	140.2	–16.3

4. Estimation of the Single-Phase Rectifier Parameters from Experimental Measurements

Since the database allows obtaining the fundamental and harmonic currents of the single-phase rectifier, it can also be used to estimate the rectifier parameters (X_L, X_C and R_D) from experimental measurements.

First, the current harmonic spectrum $\underline{I}_{h,\text{meas.}} = I_{h,\text{meas.}}\angle\phi_{h,\text{meas.}}$ of the single-phase rectifier must be obtained from the Fourier Series of its measured AC current, and the single-phase rectifier parameters X_L, X_C and R_D can then be estimated by solving the error function non-linear system of the form $\mathbf{F}(\mathbf{x}) = 0$:

Fig. 3. Supply network analyzer AR5L of CIRCUTOR.

$$
\begin{aligned}
f_1(\mathbf{x}) &= \frac{\left(I_{1,\text{meas.}} - \left(V/R_D\right) I_{1,\text{N}}\right)}{I_{1,\text{meas.}}} = 0 \\
f_2(\mathbf{x}) &= \frac{(\phi_{1,\text{meas.}} - \phi_1)}{\phi_{1,\text{meas.}}} = 0 \qquad (3) \\
f_3(\mathbf{x}) &= \frac{(\phi_{3,\text{meas.}} - \phi_3)}{\phi_{3,\text{meas.}}} = 0
\end{aligned}
$$

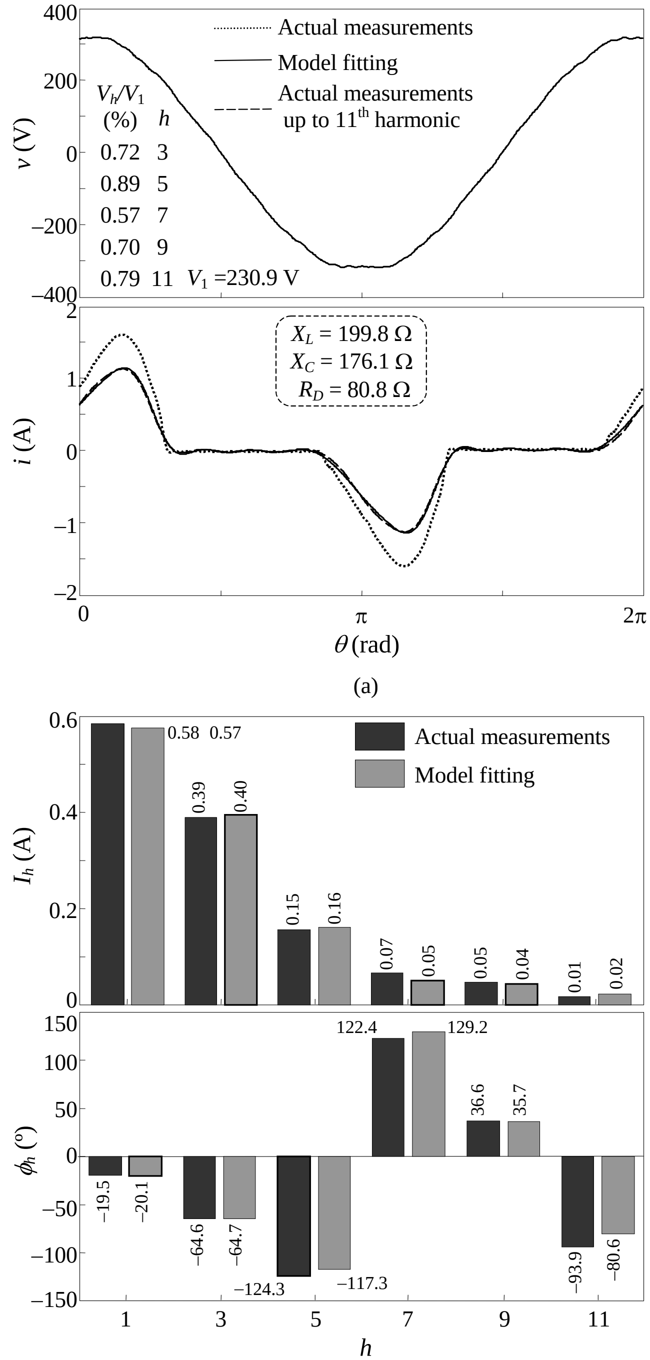
where $\mathbf{F} = (f_1, f_2, f_3)$, $\mathbf{x} = (X_L, X_C, R_D)$, and $I_{1,N} = g_{I1}(x_{L,N}) = g_{I1}(X_L/R_D)$ and $\phi_h = g_{\phi h}(x_{L,N}, x_{C,N}) = g_{\phi h}(X_L/R_D, X_C/R_D)$ ($h = 1$ and 3) are the rms and the phase angle values obtained from the database. Moreover, V is the supply voltage of the experimental measurements, which is adjustment information. It must be noted that other equations could be chosen in (3) but those proposed provided the best results.

5. Experimental Tests

Two experimental measurements were performed to validate the use of the database for single-phase rectifier parameter adjustment. The currents consumed by a personal computer (PC) and a television (TV) were measured in the laboratory with the supply network analyzer AR5L of CIRCUTOR (Fig. 3). Both devices employ single-phase uncontrolled rectifiers (Fig. 1) as their power supply.

The measured voltage and current waveforms, v and i, and the current harmonic spectrum are shown in Figs. 4 and 5, where the rectifier parameters estimated from the database are also labelled. Considering that $V \approx V_1$ and according to (2), these parameters correspond to the invariants $x_{L,N}^{(PC)} = 2.46\%$, $x_{C,N}^{(PC)} = 2.18\%$, $x_{L,N}^{(TV)} = 1.97\%$ and $x_{C,N}^{(TV)} = 2.31\%$, and the reference currents $I_R^{(PC)} = 0.35$ A and $I_R^{(TV)} = 0.26$ A ($I_R = V/R_D$). The current waveforms and the current harmonic spectrum of the fitted model are also shown in the above figures. Since the database only provides up to the eleventh harmonic current, the measured current waveform is plotted considering up to this harmonic for comparison. It can be observed that, despite the harmonic content of the supply voltage, the obtained results agree closely with the experimental measurements.

The rms values of the adjusted harmonic currents correspond to the normalized currents $I_{h,N}^{(PC)} = 1.64$, 1.12, 0.45, 0.14, 0.12, 0.06 and $I_{h,N}^{(TV)} = 1.67$, 1.20, 0.59, 0.17, 0.14, 0.08 for $h = 1$, 3, 5, 7, 9 and 11 (2). These values can be obtained by interpolation in the shaded cells of the database.



(b)

Fig. 4. PC test: a) Voltage and current waveform measurements. b) Harmonic spectrum of the PC currents

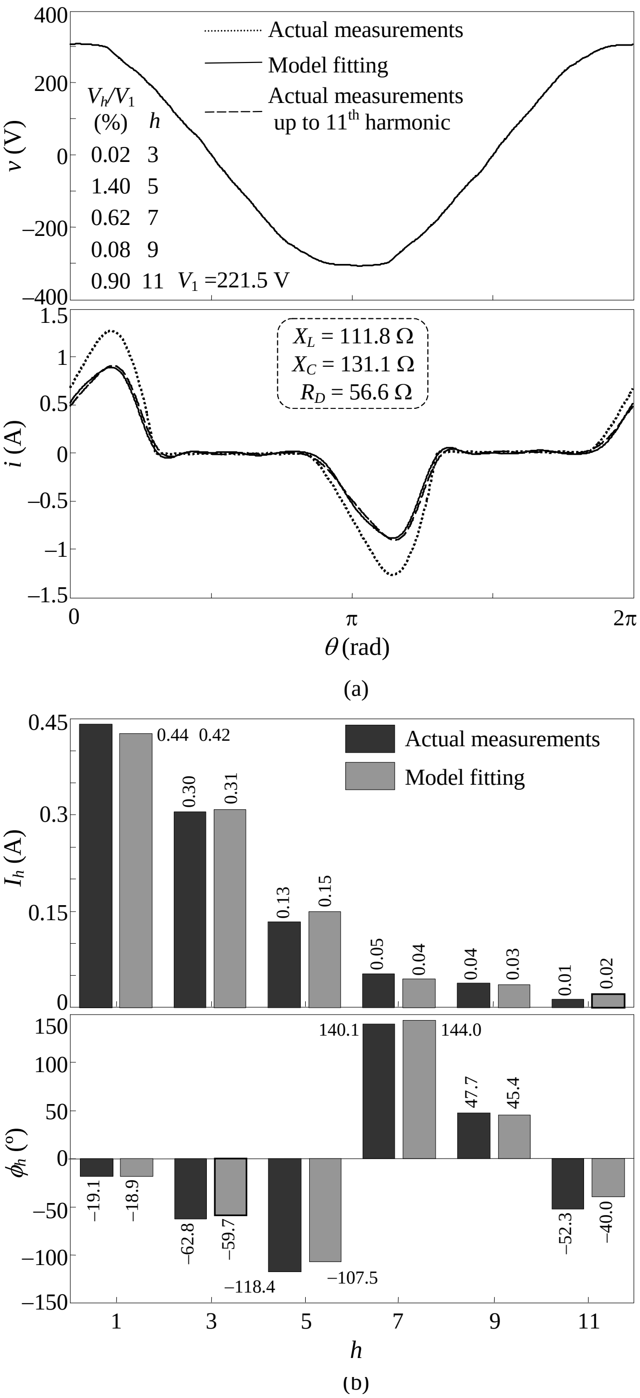


Fig. 5. TV test: a) Voltage and current waveform measurements. b) Harmonic spec

6. Conclusion

In this paper, single-phase uncontrolled rectifier parameters are estimated from experimental measurements using database of the rectifier harmonic currents (magnitude and phase angle). The current consumed by a personal computer and a television was measured and the rectifier harmonic current database was used to adjust the parameters of the single-phase uncontrolled rectifier employed by these electronic devices as their power supply.

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