Un análisis del Fenómeno de Atenuación-Amplificación en circuitos ramales para cargas residenciales.

An Investigation on Harmonic Attenuation-Amplification Effect on Home Appliances branch circuits.

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RESUMEN

Hoy en día, Electrodomésticos Eficientes basados en fuentes conmutadas son ampliamente acogidos en el sector residencial y comercial. Estas iniciativas han sido propuestas en pro de la conservación de energía y protección ambiental. Sin embargo, a pesar de que un solo electrodoméstico puede no ser relevante, en cuanto a afectación de calidad de la potencia se refiere, múltiples usuarios usando varias de estas cargas pueden causar un impacto significativo en la distorsión de corriente en sistemas de distribución de baja tensión. De esta manera, el Fenómeno de Atenuación-Amplificación toma un papel decisivo durante la estimación y la predicción. Si no se tiene en cuenta este fenómeno, la distorsión de corriente puede ser sobrestimada y la evaluación puede ser conservadora. Este trabajo propone un índice denominado Factor de Ampliación-Atenuación Total (TAF) que permite evaluar el impacto del Fenómeno sobre la Distorsión Armónica Total de Corriente (THDI). El índice TAF es utilizado sobre 1575 medidas de tensión y corriente: 15 electrodomésticos, 3 formas de onda típicas de tensión (distorsionadas y no distorsionadas), 5 regulaciones de tensión y 5 longitudes de cable de acuerdo con las condiciones de operación de circuitos ramales de baja tensión. Los resultados muestran poca incidencia sobre el fenómeno de atenuación-amplificación para una sola carga cuando se varía la longitud del circuito ramal, la distorsión y la regulación de tensión que la alimenta.

PALABRAS CLAVE: Cargas Residenciales no lineales, Distorsión armónica total, Modelado de cargas no lineales, Fenómenos de Atenuación-Amplificación y Armónicos del Sistema de Potencia.

ABSTRACT

Nowadays, the Energy Efficient Home Appliances (EEHA) based on Switch Mode Power Supply (SMPS) are widely adopted in residential and commercial sector. These initiatives have been proposed following the energy conservation and environmental protection efforts. Nevertheless, these loads consume high distorted currents in comparison with the fundamental component. A single SMPS load connected to Point Common Coupling (PCC) can be not significant. However, many users using these loads can cause a significant impact on harmonic current distortion on the distribution systems. In this way, the attenuation-amplification effect take a decisive role. If this effect is neglected, the collective harmonic current produced by the loads can be overestimated and the harmonic assessment can be conservative. This work proposes the Total Attenuation-Amplification Factor (TAF) to assess the impact of the effect on the Total Harmonic Distortion Current (THDI). The TAF index is studied considering 1575 voltage and current measurements: 15 different home appliances, 3 typical supply voltage waveforms (distorted and undistorted), 5 voltage regulations and 5 different wire length according to operation conditions of dwelling branch circuits on low voltage facility. The results show low incidence on the attenuation-amplification effect when a single load is supplied and the wire length of the branch circuit, the distortion and regulation of voltage are varied.

KEYWORDS: Home Appliances based on Switched Mode Power Supply, Total Harmonic Distortion, Harmonic analysis, attenuation-amplification effects, and Power system harmonics.

1. INTRODUCTION

The EEHA or Power Electronic (PE) interact with other loads and the system equivalent impedance in Low Voltage (LV) distribution network (background voltage distortion). These interactions are known as attenuation-amplification and diversity effects and can produce a decrease/increase of current harmonic distortion, losses and low efficiency [1] [2]. The attenuation-amplification is defined as the interaction between distorted voltage and current and the equivalent impedance [3]. The diversity is define as the partial cancellation of total harmonic current produced by different loads connected at the PCC. This cancellation is caused by the dispersion in phase angles, which is related to the load characteristics, demand variations and power factor [4] [5].

Some papers described attenuation-amplification effect using different PE devices, and specifically the EEHA based on SMPS under sinusoidal operation conditions. For instance, typical SMPS loads: Personal Computer (PC), Fluorescent Lamp (FL) and Laptop are analyzed together with Incandescent Lamp (IL) to study the harmonic cancelation effects due to mixing linear and non-linear loads in [6]. A Controlled Voltage Source (CVS) is used to separate the effects of the grid supply voltage. However, the effects of wire length and typical voltage distortion are not considered.

For Compact Fluorescent Lamp (CFLs), extensive measurements are carried out considering the wire length variation and the background distortion produced by several CFLs connected in parallel configuration. Nevertheless, the measurements are not performed under controlled conditions using distorted supply voltage and constant impedance on CVS [7]. Thus, an index is proposed to characterize the Attenuation effect on CFLs. However, this Index does not allow easily quantify the attenuation-amplification effect impact on the THDI [8].

Also, in the assessment area of energy efficiency, the research in [1], [9] and [10] analyze PE devices, Electric Vehicle Battery Chargers (EVBC), and Photovoltaic Inverters (PV inverters), respectively. These works assess the operating mode impact of these loads in different operating conditions. The results exhibit strong power-dependency of their harmonic performance, indicated by a change (i.e. increase) in harmonics emission in low-power operating modes.

Moreover, these works emphasize the need to include tests for modern PE devices with more operating conditions that the sinusoidal waveforms to check the harmonic distortion in practical applications.

This paper studies the attenuation-amplification effect and carries out an empirical investigation on 15 home appliances. The analysis includes the TAF index, proposed in this paper to assess the attenuation-amplification effect when is varied the wire length, the distortion and the regulation of supply voltage.

The paper is organized as follows: Section 2 describes the process for the test and measurements carried out. In Section 3 the TAF Index formulation are addressed. Next, the Section 4 describes the analysis of research results. Finally, in Section 5, the conclusions from this research are presented.

2. TEST AND MEASUREMENTS

2.1. Selection and Classification of Home Appliances

In order to carry out a representative study, home appliances from typical residential loads in Colombian households are selected considering easy access, availability and costs. In this way, in Table 1, the National Administrative Department of Statistics DANE classifies the most commonly used home appliances in: Conventional CRT TV, Sound equipment, DVDs, monitors, desktop PCs and Laptops.

Table 1. Colombian households Percentage with PE devices

Appliance	P [W]	Nacional [%]	Bogotá [%]
Microwave	1080	20.3	36.1
CRT TV	100	77.7	76.5
TV LED	100	28.5	44.9
DVD	19	44.7	57.7
Sound Equipment	75	47.4	58.8
Video cam	24	21.1	36.4
PC Screen	48	26.1	39.7
Desktop PCs	475	26.1	39.7
Laptops	93	23.3	36.7
Cellphone	15	94.7	96.3

Font: DANE, Encuesta nacional de calidad de vida 2013. [11]

The EEHA also can be classified according to the internal topologies, i.e. Non-electronic and Power Electronic devices. The Non-electronic can be resistive (in phase), inductive (lagging phase), capacitive (leading phase) or their combination [12]. The PE devices category is based on the circuit components of the Power Factor Correction circuit (PFC). According to the PFC topology, the PE devices can be classified as:

NO-PFC, PFC-passive and PFC-active. The NO-PFC usually have a bridge rectifier and a dc link capacitor.
The PFC-passive devices have additional capacitors or inductors to improve the PF and in turn the current distortion. The PFC-active correspond to low-power devices such as computer supply voltage, and battery chargers for electric vehicles. These use an active PFC with different DC-DC converters to obtain a quasi-sinusoidal current waveform with a THDI generally below to 10%. Moreover, according to the functionality, the home appliances also can be classified in: Power Electronic devices (based on SMPS), Energy efficient lighting devices, Resistive loads and directly connected motors [14]. This work focuses on the category of Power Electronic devices and directly connected motors.

2.2. Test Design

From Figure 1, the impedances of the branch circuit and the Controlled Voltage Supply (CVS) (upstream to bus B1) are modeled through Req + jXeq and the variable length-impedance of wire by R+jX. In this way, the Attenuation-Amplification Effect can be explained as the variation of current distortion in comparison with the initial current on sinusoidal conditions when the harmonic input current Iin flows through these impedances causing a new harmonic voltage drop that is added to Vs. This new voltage distortion is measured in V and it causes a new harmonic current distortion measured in A. This variation on current distortion is called attenuation-amplification effect.

The test proposes in this paper studies a scenario where the main feeder is split into branch circuits, which in turn supplies several home appliances. In this case, a single load is connected to the source, at the same time. The aim is to analyze the variation incidence of wire length and voltage regulation on Attenuation-Amplification Effect on different voltage distortion conditions, and in this sense, the harmonic current distortion produced by the home appliances connected to the branch circuit.

The test is composed for two stages: In the first stage, the laboratory measurements are performed for a total of 1575 different current and voltage signals: 3 typical waveforms, 5 wire length and 7 supply voltage regulations for 15 linear and non-linear home appliances.

For the second stage, the measurements are analyzed finding the incidence of wire length and voltage regulation on attenuation-amplification effect.

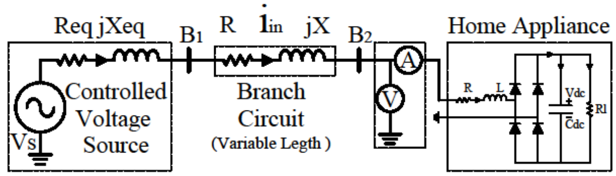

Figure 1. Experiment Design: Modeling and measurements

The voltage waveforms used in this work provide actual conditions present in a residential, commercial and industrial facilities. In where, the sinusoidal waveform is used as reference, the flat-top waveform models the voltage distortion caused by the massive adoption of single-phase rectifiers on residential loads, and the pointed-top waveform is related to six-pulse rectifiers voltage distortion, widely adopted in industrial sector.
The Table 2 presents the harmonic spectrum of the flat-top and pointed-top waveforms used in the test. These are adopted from [15] for measurements on 120 V 60 Hz.

Table 2. Harmonic Spectrum of the supply voltage waveforms

Voltage Harmonics	Order	Sinu	Flat-top	Pointed
Magnitude (Vrms)	1	120	116.61	120
	3	-	2.76	3.65
	5	-	1.93	3.65
	7	-	1.04	0.06
Angle (°)	1	0	0	0
	3	-	0	180
	5	-	180	0
	7	-	0	0
THDV		≈0	3.03	4.30

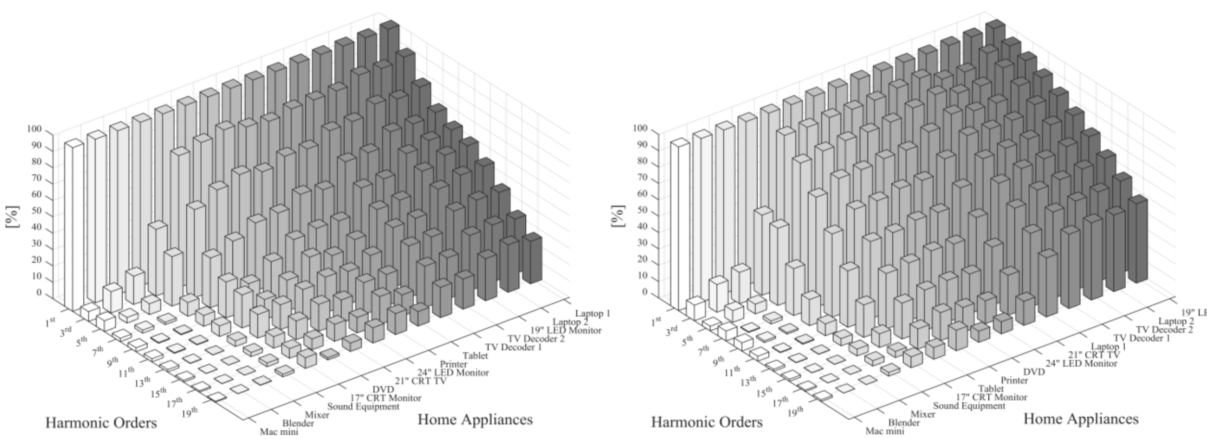

Figure 2. Home Appliances Current on Flat-Top and Pointed-Top Supply Voltage. Regulation 0% and Wire Length 0m

The Figure 2 and Figure 3 shows the harmonic current spectrum for different voltage supply conditions. In the figures the home appliances are ordered from highest to lowest according to their individual THDI. For example, in the Figure 2, for Flat-Top (left side) and for Pointed-Top Supply Voltages (right side), the Laptop 1 (183.52%) and 19” LED Monitor (240.02%) have the hightest THDI. While, the Mac Mini has the lowest THDI (10.15% and 13.88%) in both voltage conditions. This is lower than even the linear loads (Blender and Mixer). This behaviour indicates a PFC-active in its topology. Thus, in Figure 3 and Table 3, the Mac Mini THDI increases (188.83%) on sinusoidal voltage with respect to others distorted voltage conditions. This behaviour can be related to the power-dependency of harmonic performance in PE devices described in [1] [9] and [10], since the Power in these conditions (0% of voltage regulation, 0m of wire) is lower (18W, See Table 3) than others operating conditions.

Table 3. Home Appliances Data from Experimental tests on Nominal Sinusoidal Supply Voltage

No.	**Home App.**	**P [W]**	**THD V [%]**	**THD I [%]**	**Irms [A]**	**I1 [A]**	**PF**	**PF disp**
1	DVD	8	0.04	150.2	0.12	0.05	1.0	0.55
2	Sound Equip.	12	0.07	65.0	0.13	0.07	0.9	**0.76**
3	19" LED Monitor	11	0.12	**203.5**	0.21	0.06	1.0	**0.43**
4	17" CRT Monitor	58	**0.27**	136.7	0.83	0.34	1.0	0.58
5	24"LED Monitor	18	0.12	153.3	0.29	0.11	1.0	0.53
6	Mac mini	18	0.13	**188.8**	0.33	0.10	1.0	0.46
7	Blender	140	0.12	**15.8**	1.28	0.89	0.9	0.91
8	TV Deco. 1	6	0.09	190.4	0.11	0.03	1.0	0.44
9	TV Deco. 2	6	0.09	189.7	0.11	0.03	1.0	0.45
10	Printer	6	0.10	186.0	0.12	0.04	0.9	0.44
11	Mixer	47	0.08	20.3	0.48	0.33	0.8	0.82
12	Laptop 1	41	0.22	172.2	0.70	0.25	1.0	0.48
13	Laptop 2	28	0.20	196.7	0.54	0.18	1.0	0.44
14"	21" CRT TV	50	**0.27**	163.3	0.80	0.30	1.0	0.52
15	Tablet Charger	12	0.07	121.8	0.16	0.07	1.0	0.61

The Table 3 presents the results for the home appliances tested on sinusoidal supply voltage, 0m wire length and 0% of voltage regulation. The THDV in Bus B2 is equal to 0.27% for 17"-21" CRT Monitor, despite a sinusoidal supply voltage is fixed in the CVS, the impedance upstream to Bus B2 (B1 = B2 for 0m wire length, See Figure 1) causes a drop voltage and an increase of voltage distortion or Amplification Effect on Bus B2 (See THDV in Table 3). Moreover, the highest THDI correspond to 203.5% for 19" LED Monitor and the lowest for the Blender with 15.8%.

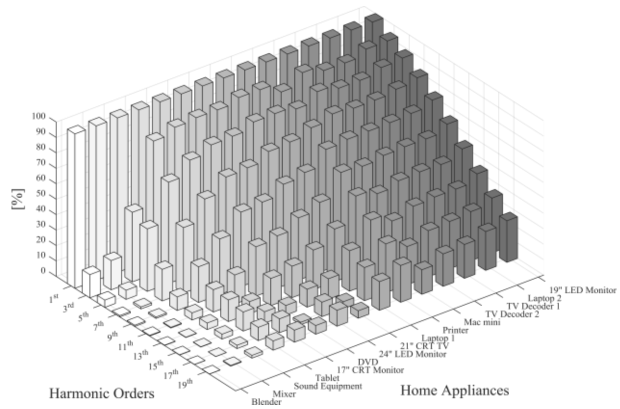

Figure 3. Current Respond Magnitude of Test Home Appliances on Sinusoidal Supply Voltage.

The Total Power Factor PF is compute from (1), as the relation between the Active Power (P), energy transmitted to the load, and the Apparent Power (S), max. energy that could be transmitted.

$$PF = P/S \tag{1}$$

Where the Active Power is equal to:

$$P = V_{RMS} \times I_1 \times \cos\Theta \tag{2}$$

And Θ is the angular difference between voltage and current.

The Apparent Power can be define as:

$$S = V_{RMS} \times I_{RMS} \tag{3}$$

In this way, for non-linear home appliances the Total Power Factor also can be defined as:

$$PF = PF_{dist} \times PF_{disp} \tag{4}$$

And the Distortion Power Factor (PFdist) and Displacement Power Factor (PFdisp) as:

$$PF_{dist} = \frac{PF}{PF_{disp}} = \frac{P/S}{\cos\Theta} \tag{5}$$

From (5):

$$PF_{dist} = \frac{V_{RMS} \times I_1 \times \cos\Theta}{V_{RMS} \times I_{RMS} \times \cos\Theta} = \frac{I_1}{I_{RMS}} \tag{6}$$

$$PF_{dist} = \frac{I_1}{I_{RMS}} = \frac{I_1}{\sqrt{\sum_{h=1} I_h^2}} = \frac{I_1}{\sqrt{I_1^2 + \sum_{h\neq 1} I_h^2}} \tag{7}$$

$$PF_{dist} = \frac{I_1}{I_1} \Bigg/ \frac{\sqrt{I_1^2 + \sum_{h\neq 1} I_h^2}}{I_1} = 1 \Bigg/ \sqrt{\frac{I_1^2}{I_1^2} + \frac{\sum_{h\neq 1} I_h^2}{I_1^2}} \tag{8}$$

$$PF_{dist} = 1 \Bigg/ \sqrt{1 + \sum_{h\neq 1} \frac{I_h^2}{I_1^2}} = \frac{1}{\sqrt{1+THDI^2}}$$

From (5):

$$PF_{disp} = \sqrt{1+THDI^2} \times PF \tag{9}$$

The equation (9) is used to compute the Displacement Power Factor (PFdisp) from the Total Power Factor (PF) in Table 3. For all non-linear home appliances the PF is relative high (near to 1). However, the PFdisp is much lower and vary from 0.43 (19" LED Monitor) to 0.76 (Sound Equipment) in PE devices tested.

In this way, according with Table 3, the distorted supply voltage conditions on several non-linear home appliances can cause a significat impact on power factor and current harmonic distortion of low voltage distribution systems.

3. THE TAF INDEX

The Total Attenuation-Amplification Factor (TAF index) is proposed to characterize the impact of the attenuation-amplification effect of all harmonics, on THDI. Other proposals in [4], [7] and [8] assess the attenuation effect per harmonic order, nevertheless, the relation of the effect with THDI is not taken into account. For the disaggregation of TAF Index, the THD definition in Std IEEE 519-2014 are used in equations (10) and (11):

$$THDI = \frac{\sqrt{I_3^2 + I_5^2 + I_7^2 + I_9^2 + \ldots + I_h^2}}{I_1} \tag{10}$$

$$THDI_{DIST-REF} = \sqrt{\sum_{h\neq 1} I_h^2} \Big/ I_1 \tag{11}$$

From (10) and (11), (12)

$$\frac{THDI_{DIST}}{THDI_{REF}} = \frac{\sqrt{\sum_{h\neq 1} I_{h\_dist}^2}}{I_{1\_dist}} \Bigg/ \frac{\sqrt{\sum_{h\neq 1} I_{h\_ref}^2}}{I_{1\_ref}}$$

In where, I_{h_dist} and I_{1_dist} are the harmonic order and fundamental current responses to distorted supply voltage, respectively. Similar definitions are proposed for I_{h_ref} and I_{1_ref} for the reference supply voltage, for this work, the reference voltage is approximately sinusoidal. Thus, TAF index is define in (13) as:

$$TAF = \left[\sqrt{\sum_{h\neq 1} I_{h\_dist}^2} \Big/ \sqrt{\sum_{h\neq 1} I_{h\_ref}^2} \right] \tag{13}$$

From (12),

$$THDI_{DIST} = TAF \times \left[\frac{I_{1\_ref}}{I_{1\_dist}} \right] \times THDI_{REF} \tag{14}$$

When the fundamental components are equal:

$$THDI_{DIST} \approx TAF \times THDI_{REF} \tag{15}$$

In this way, the TAF Index is defined as the ratio between the square root of harmonics mean square (without fundamental) for a supply voltage distortion and the sinusoidal voltage waveform (reference case). This ratio is weighted in turn by the relation by the fundamental component of reference signal compared to fundamental of non-sinusoidal supply voltage. The factor becomes above one, if the THDI of the load increase for a specific supply voltage distortion with respect to reference.

4. RESULTS AND ANALYSIS

For this section, the variation of wire length and voltage regulation are analyzed in independent way in Subsections 4.1 and 4.2, respectively.

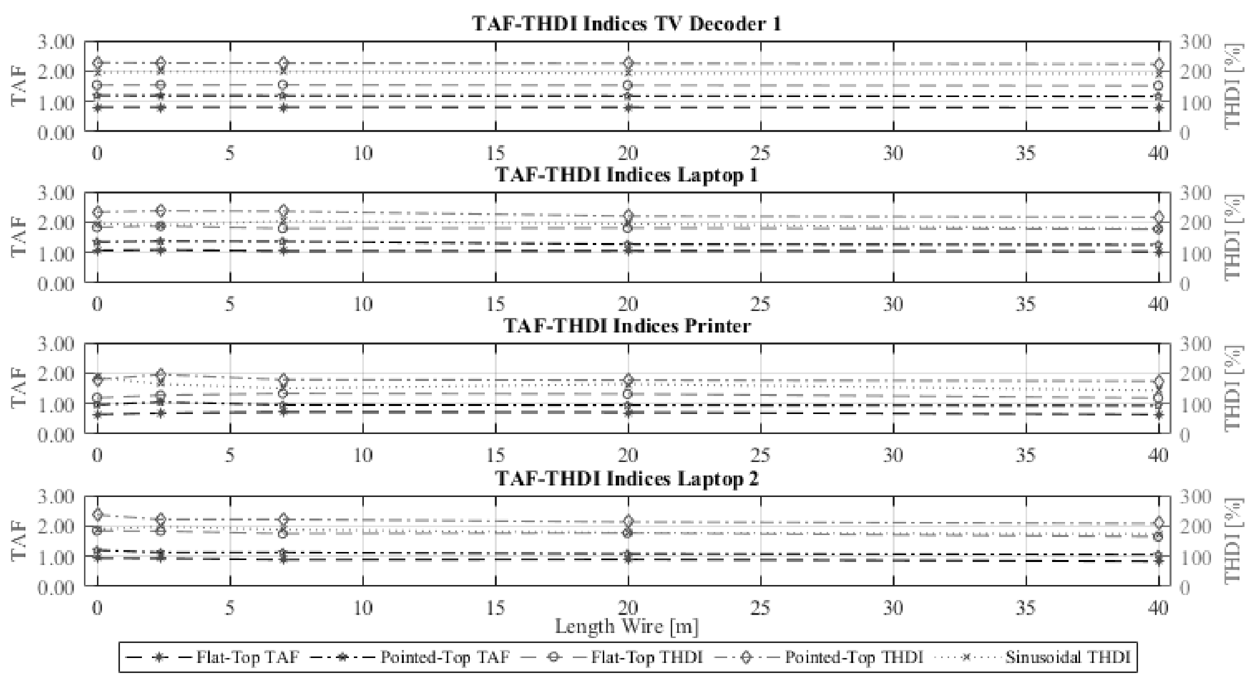

Figure 4. Incidence of Wire Length variation on -3% Voltage Regulation

4.1. Wire Length Incidence

According with NFPA 70 (National Electrical Code), typical branch circuits use wires gauge No. 12 AWG and there is not restriction on the length. In this work, a maximum wire length is defined in 40 m with 4 intermediate power outlets at 20 m, 7 m, 2.4 m and 0 m. The variation incidence of wire length for a fixed Voltage Regulation of -3% is showed in Figure 4, where, the Index exhibit a slightly decrease when this is increased.

For all home appliances studied on pointed-top voltage, the TAF Index (left-side and bold lines) describes an Amplification Effect (TAF > 1). The TV Decoder 1, Laptop 2 and Printer describe an attenuation effect on flat-top supply voltage.

From the experiments are possible to conclude that the amplification-attenuation effect are not significant with only the incidence of wire length, since the voltage distortion is not high enough for a single PE device. Nevertheless, a greater rated power, a low power consumption or a high voltage distortion as Pointed-top supply voltage can cause an significant increase on the Amplification Effect.

4.2. Voltage Regulation Incidence

The variation of voltage regulation is defined according to Colombian Normative NTC 1340 (+5% to -10% of Nominal Voltage). For this work, seven (7) positions of voltage regulation (-5%, -3%, -1%, 0%, +1%, +3%, +5%) are used in the experiments.

The variation incidence of voltage regulation with a constant wire length (7 m) are showed in Figure 5 for 19" LED Monitor, 17" CRT Monitor, 24" LED Monitor and 21" CRT TV. These exhibit a slight increase of Indices as voltage regulation increase. Thus, on left-side and bold lines of Figure 5, again for the pointed-top voltage, an Amplification Effect is present (TAF Index >1), while for flat-top voltage an attenuation effect is showed (TAF Index < 1).

From these experiments are possible to conclude that the amplification-attenuation effect remains approximately constant with only the incidence of standardized voltage regulation because the voltage distortion is not significant for a single home appliance supplied.

5. CONCLUSIONS

The mass adoption of PE devices can cause a significant problem on power factor and current distortion on low voltage distribution systems. The experiments report a low Displacement Power Factor and an important increase of THDI in low power operating conditions in home appliances with PFC-Active.

The TAF index is proposed to quantify the impact of attenuation-amplification effect on total harmonic distortion, these results help to understand the overestimation on THDI and the impact under the harmonic assessment when it is not considered the attenuation-amplification effect.

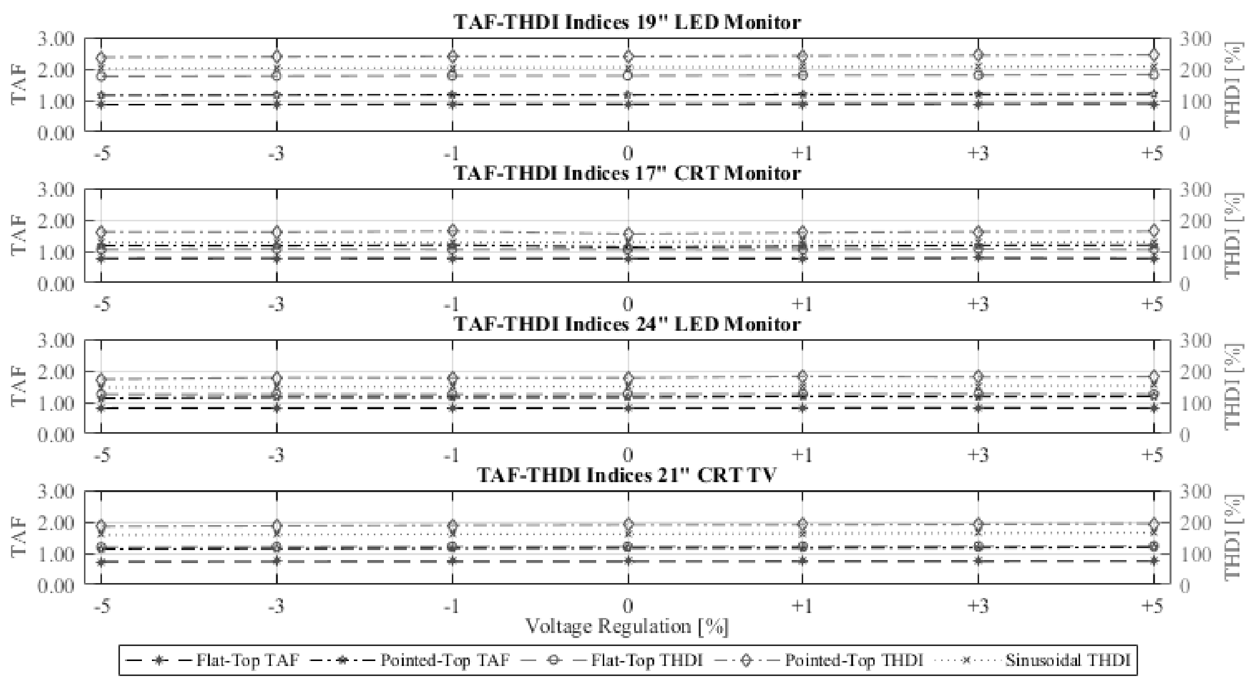

Figure 5. Incidence of Voltage Regulation variation on 7m Wire Length

From the experiments are possible to conclude that the amplification-attenuation effect is not significant with only the variation incidence of wire length and voltage regulation, since the voltage distortion in both cases is not significant for a single home appliance supplied.

However, a greater voltage distortion as the Pointed-top supply voltage, several home appliance connected to the same PCC or PE devices with a high current demand can be significant for the attenuation-amplification effect.

For future works, more study cases and measurements on different power and voltage operation conditions must be carried out, in order to analyze the impact of multiples PE devices on the amplification-attenuation effect and the possible impact of power dependency in the total harmonic distortion on several user connected in low voltage grid.

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