Impact of the Load Usage Context on Harmonic Generation

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***Abstract* — Harmonic contents are a growing concern in actual power systems. This fact is related to the increasing participation of power electronics in a wide area of appliances, work environment equipment as well as industrial applications. In this perspective, this work looks at the interaction between the harmonic generation and the usage context in which it occurs, presenting a comparison case between household and work environments. For this sake, real data and measurements were used to perform the environments modeling. Further, simulations were held for low, average and high occupancy rates. The results provide significant information about the influence of the environment on the generation of harmonics and how the harmonic components and equipment weigh on it.**

***Keywords* — Appliances, harmonic generation, household, load usage context, work environment.**

I. Introduction

The increasing participation of power electronics in a wide area of equipment's ranging from home and work environments appliances to industrial machines are generating a growing concern regarding the harmonic injection over the system.

Harmonic components are usually generated as an adverse effect of power electronics applications. Its presence leads to a series of problems for the system as increase in energy consumption, operation of protection devices, metering inaccuracies [1], electromagnetic interference, overload, voltage droop, flicker and interruption [2]. Equipment related problems like overheating, life reduction and premature failure are also reported

The distortion created by these components worsen the system power quality affecting indicators as $THD_{V,I}$ and $IHD_{V,I}$ [3], leading to indirect economic losses as active and reactive losses increase [4]-[5] or directly assigned in cases of interruption and equipment failure. Contextualization of harmonic penetration in distribution networks due to household and work environments loads are presented in [4]-[5].

The literature presents several cases of studies regarding harmonic impact and influence determination. In [4] the harmonic losses in a university research building are determined. Reference [5] investigates the influence on losses of harmonic components injected by appliances in a residential distribution system. References [6]-[8] determine the major harmonic component contributor to feeder voltage distortion, whereas [9] concerns about harmonic distortions in hosting capacity of distributed generation (DG) studies.

This work focuses on the interaction between the harmonic generation and the context in which it occurs. In this sense, a comparison between two different systems environments, household and workplace, is featured.

For this sake, real data provided by [10]-[12] and measurements were associated to perform the modeling of the environments. Further, simulations were held for three different occupancy rates (low, average and high) in order to ensure consistency to the results.

At last, the results provided meaningful information determining the impact of the environments on the generation of harmonics; the harmonic components and equipment influence on the harmonic injection; and the differences and similarities of the analyzed contexts from the perspective of harmonic generation.

II. Household environment

Houses modelling is a process that seeks to replicate a real house consumption. The prediction of its appliances operating status depends on a large number of personal conditions that are empirically determined. For this sake, benchmark data from pattern of residents' consumption [10]-[12] are employed to determine home appliances operating status and generate different consumption scenarios in an annual base.

A. *Household Patterns of consumption*

The housing modelling process consists in determine which appliances are presents in a household and reach the housing energy consumption target associate to these appliances. The house consumption is a variable that suffers from a diversity

The authors thank FAPEMIG, CAPES, CNPq and INERGE for partially supporting this work.

of factors [12]-[13], being the most important the number of people living in the house, income, season and location. In this sense, different houses consumption needs to be applied to represent these different possibilities.

The consumption patterns data are used in this process to determine how many hours each equipment operate per year helping to achieve the annual housing energy consumption target [13]. These data are acquired by measurements, surveys and other sources such manufacturers and electricity distribution companies that assists in the appliance usage determination.

The household's appliances equivalent usage for the three energy consumption scenarios are expressed in Table I.

TABLE I. HOUSEHOLD APPLIANCES USAGE

	Hours of operation per year (h)		
Loads	*Low Energy Consumption*	*Average Energy Consumption*	*High Energy Consumption*
Fridge	3100	3713	6197
Freezer	0	1722	3900
CLF	67664	116593	270163
TV	4432	4714	8732
Laptop	2136	2291	5205
Desktop	2356	2481	4144
Washer	120	150	302
Dryer	144	190	480
Microwave	120	120	120

III. ANALYZED WORK ENVIRONMENT

The analyzed work environment is the Centre of Excellence in Smart Grids, CERIn, located at Federal University of Itajuba – Brazil. To produce its representation, actual measurements were held on the analyzed workplace for low, average and high occupancy rates. These measurements led to three different demand scenarios depicted in Fig. 1.

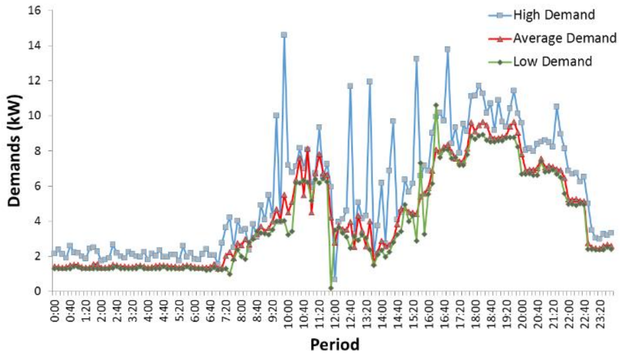


Fig. 1. High, average and low occupancy rates [4]

Occupancy rates are defined as an index of the actual level of use of the facility for an entire day period.

A. Workplace Patterns of consumption

Based on demand data and in association to the loads usage patterns experimentally observed at CERIn, different operating points were performed and a demand representation for the occupancy scenarios by equipment's operating hours was developed. This new representation employs actual data of the number of equipment present in CERIn and their volume of operating hours providing, further they are combined in order to develop the equivalent representation presented in Table II.

TABLE II. WORKPLACE APPLIANCES USAGE

	Hours of operation per year (h)		
Loads	*Low Occupancy Rate*	*Average Occupancy Rate*	*High Occupancy Rate*
Ballast Lamp	388342	435482	611813
Printer	27959	34906	45418
Desktop	92327	103027	159578
Telephone	27959	34906	45418
CLF Lamp	20683	20683	55967
Fridge	6144	6144	8760

IV. METHODOLOGY

This paper aims to determine whether different environments influence the harmonic behavior and in which level. In this sense, household and workplace environments were considered and analyzed for different energy consumption scenarios in order to determine the equipment and harmonic components parcel of influence in the total harmonic generation of each environment.

For this sake, measurements were held to determine equipment harmonic profiles and execute their modelling. From patterns of usage, energy consumption and occupancy rates the annual equipment's hours of operation were obtained, and the household and work environments modelled.

Executed those aspects, analyses were held for the different scenarios and the following contributions are presented:

The first contribution is the determination of each equipment participation in the total harmonic generation for each analyzed environment.

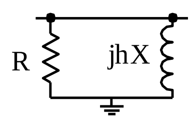
The second contribution is the determination of the influence portion of each harmonic component in the total harmonic generation for each environment.

The third and main contribution of this work is the comparison between household and workplace environments, indicating how equipment's and harmonic component influence (weights) on their harmonic generation. This helps to understanding how harmonics interact within power systems and in the determination of measures to reduce their impact.

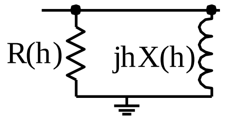
A. Load Modeling

In the literature, several load models for harmonic studies are presented [15]-[16]. The most common/recommended linear load models for harmonic studies are shown in Table III.

TABLE III. LINEAR LOAD MODELS FOR HARMONIC STUDIES

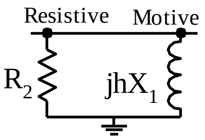
Model	Parameters
Model 1. Parallel 	$R = \frac{V^2}{P}$ $X = \frac{V^2}{Q}$

Model 2. Skin effect.



$$R(h) = \frac{V^2}{m(h)\cdot P}$$
$$X(h) = \frac{V^2}{m(h)\cdot Q}$$
$$m(h) = 0.1\cdot h + 0.9$$

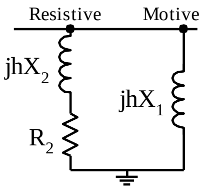
Model 3. Induction motor plus Resistive



$$R_2 = \frac{V^2}{(1-K)\cdot P}$$
$$X_1 = \frac{V^2}{K_m K_1 K\cdot P}$$

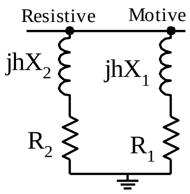
K_m is the install factor (≈1.2)
K_1 is the severity factor (≈8), and
K is the fraction of motor load.

Model 4. CIGRE/EDF



$$R_2 = V^2/(1-K)\cdot P$$
$$X_2 = 0.073\cdot R_2$$
$$X_1 = \frac{V^2}{K\cdot P\cdot(6.7\cdot\tan\phi - 0.74)}$$
$$\tan\phi = Q/P$$

Model 5. Inclusion of load transformer and motor damping.



X_1 and R_2 as in Model 4.
$$X_2 = 0.1\cdot R_2$$
$$R_1 = X_1/K_3$$
K_3 is the effective quality factor of the motor circuit (≈8 for large motors).

In this study, a non-linear model was adopted. It is featured in Fig. 2 representing loads up to its 27th harmonic component using current sources as recommended by the IEEE 519 (utility version) [14] to cases where the maximum voltage distortion is equal to or less than 10%. To obtain the equipment's harmonic profile, measurements with DRANETZ Power Explore Px5 were performed and data provided in [11] were used.

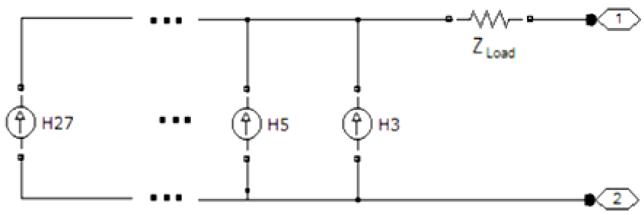


Fig. 2. Load Model [4]

In Fig. 3 a representation of the harmonic components share of influence in the total harmonic insertion generated by each equipment is presented.

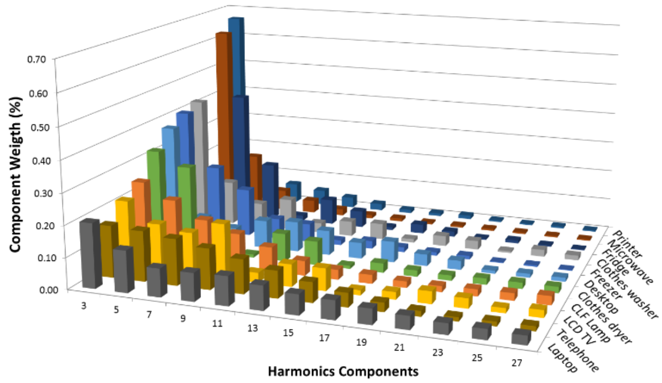


Fig. 3: Harmonic components weight in the equipment's total harmonic generation

B. System Modeling

The distribution system is responsible for low and medium energy customer's connection to the transmission system. It is constituted by primary and secondary systems separated by a service transformer.

In this work, its modeling is performed by a Multi Grounded Neutral (MGN) topology as shown in Fig. 4.

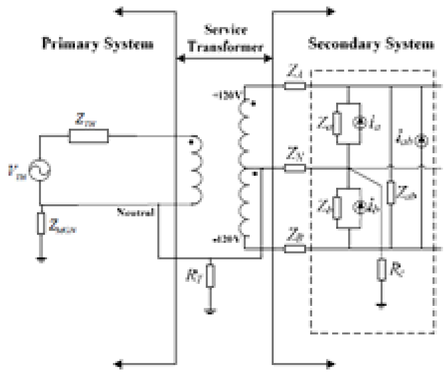


Fig. 4: System modeling [5]

V. Results

Based on equipment's annual operating hours in household and workplace environments, analyses were held to determine their harmonic behavior, being the results divided in three sections. The first focuses on the household environment analysis. Second presents the workplace environment results, while the third features a comparison between the analyzed environments.

A. Household Environment

The simulations performed indicates that household's environments are most influenced by harmonics generated by lighting equipment, that in these environments are typically provided by CFL lamps. As expected, 3rd harmonic component is the greater harmonic influencer driven by the CLF elevated number of operating hours. Although it is important to notice the significant share of 5th harmonic representing in the average energy consumption scenario 18% of the total harmonic generated in a household environment. These results are described in Table IV.

TABLE IV. HOUSEHOLD AVERAGE ENERGY CONSUMPTION APPLIANCES AND HARMONIC COMPONENTS INFLUENCE

Harmonic Component	*CLF lamp*	*Laptop*	*Desktop*	*Fridge*	*Microwave*	*Washer*	*TV*	*Dryer*	*Freezer*	***Complete Profile***
3rd	21.3%	1.3%	1.2%	0.3%	0.7%	0.3%	0.2%	0.1%	0.4%	25%
5th	15.5%	0.9%	0.3%	0.9%	0.2%	0.1%	0.1%	0.0%	0.2%	18%
7th	11.9%	0.6%	0.2%	0.4%	0.1%	0.1%	0.1%	0.0%	0.2%	13%
9th	8.5%	0.6%	0.3%	0.0%	0.0%	0.1%	0.2%	0.0%	0.1%	10%
11th	5.1%	0.6%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	6%
13th	3.4%	0.5%	0.3%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	4%
15th	3.1%	0.4%	0.2%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	4%
17th	2.2%	0.4%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	3%
19th	2.0%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3%
21th	2.4%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3%
23th	2.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3%
25th	3.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3%
27th	3.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3%
Appliance Influence	84%	6%	3%	2%	1%	1%	1%	0%	1%	

To better observe the influence portion of each harmonic component in the total harmonic generation and the appliances responsible for them, the results presented in Table IV are illustrated in Fig. 5. In that figure, *'Complete Profile'* adds up the influence portion of each harmonic component in the total harmonic generation.

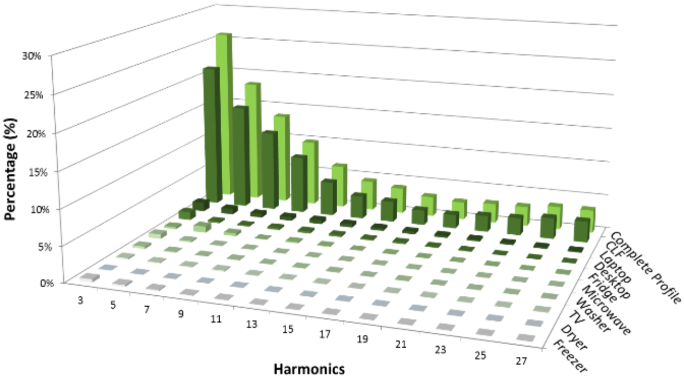


Fig. 5: Harmonic components weight in the total harmonic generation of a household environment for the average energy consumption scenario

In addition to the harmonic components distributed influence presented in Table IV and Fig. 5. A view from the perspective of the appliances' individual contribution in the total harmonics insertion is presented in Fig. 6.

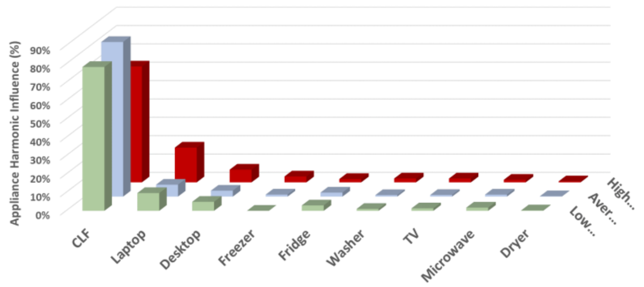


Fig. 6: Appliances influence in the total harmonic generation of a household environment for the average energy consumption scenario

It is possible to clearly observe that the biggest responsible for the harmonic generation in a household environment are CLF lamps. However, it is important to notice that this scenario begins to change when a significant increase in energy consumption is featured.

A higher energy consumption is driven by an increase in the number of appliances and consequently their hours of operation, when in comparison to lower energy consumption scenarios. This situation is well observed in Fig. 6, the high-energy scenario presents a greater share related to laptops in the total harmonic insertion, in the face of decreasing CLF lamp influence.

B. Work Environment

In work environments, the majority of appliances are constituted by desktops as may be observed in its volume of annual operating hours. This situation plays a great influence in the harmonic profile generated in workplaces.

Another important consideration regarding this kind of environment is related to the equipment used to lighting. Different from households that typically uses CLF lamps, workplaces employ a mix of lighting equipment as ballast and CLF lamps, being majorly executed by ballast lamps due to their better fit to this kind of environment. The adoption of ballasts instead of CLF Lamps exerts great influence over the weight of lighting in the total harmonic generated by a work environment, once ballast lamp harmonic injection is much lower than CLF lamp.

The total harmonic generated in a workplace environment shown by the influence portion of each harmonic component in the total harmonic generation is depicted in Table V and illustrated to the average energy consumption scenario by Fig. 7.

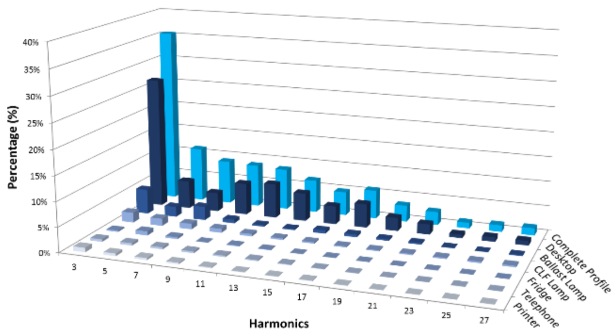


Fig. 7: Harmonic components weight in the total harmonic generation of a workplace environment for the average energy consumption scenario

TABLE V. HOUSEHOLD AVERAGE ENERGY CONSUMPTION APPLIANCES AND HARMONIC COMPONENTS INFLUENCE

Harmonic Component	*Desktop*	*Ballast Lamp*	*CLF Lamp*	*Printer*	*Telephone*	*Fridge*	***Complete Profile***
3rd	26.7%	5.1%	2.0%	0.9%	0.5%	0.3%	35%
5th	5.8%	2.1%	1.5%	0.5%	0.5%	0.8%	11%
7th	3.9%	2.8%	1.1%	0.4%	0.4%	0.4%	9%
9th	6.5%	0.8%	0.8%	0.3%	0.3%	0.0%	9%
11th	7.0%	0.3%	0.5%	0.2%	0.3%	0.2%	8%
13th	5.7%	0.2%	0.3%	0.1%	0.2%	0.1%	7%
15th	3.7%	0.6%	0.3%	0.1%	0.1%	0.0%	5%
17th	4.8%	0.5%	0.2%	0.1%	0.1%	0.1%	6%
19th	2.7%	0.3%	0.2%	0.0%	0.1%	0.0%	3%
21th	2.1%	0.3%	0.2%	0.0%	0.0%	0.0%	3%
23th	0.7%	0.1%	0.2%	0.1%	0.0%	0.0%	1%
25th	0.9%	0.1%	0.3%	0.0%	0.0%	0.0%	1%
27th	0.9%	0.2%	0.3%	0.0%	0.0%	0.0%	1%
Equipment Influence	71%	13%	8%	3%	3%	2%	

The total harmonic insertion of work environments described by appliances influence is shown in Fig. 8.

It presents desktops as the major contributor to harmonic injection in an almost stead level independently of the energy consumption scenario.

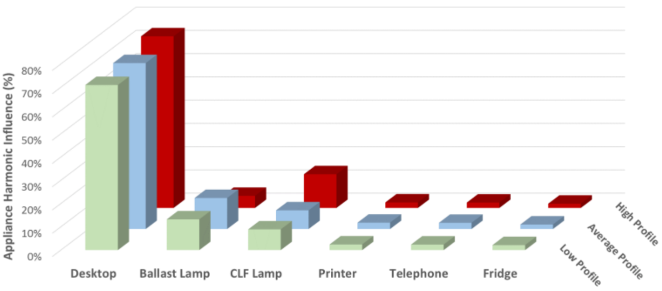


Fig. 8: Appliances influence in the total harmonic generation of a workplace environment for the average energy consumption scenario

However, variations in the energy consumption imply changes in the lighting share. As may be observed, CLF Lamps influence increase significantly in the high-energy consumption scenario. This fact is not necessarily caused by an overall reduction of ballast lamps use. Actually, due to the significant CLF harmonic generation, even with ballast lamp posing a higher rate of use in comparison to CLF lamps, a small increase in their use rate leads to a significant increase in their percentile influence in the environment harmonic generation.

C. Environments Comparison

Finally, a comparison between the analyzed environments harmonic profile is presented in Table VI. It is possible to observe that 3rd harmonic is the greater harmonic component influencer in both environments, although its level of influence is much higher in a workplace environment compared to a household. This fact is due to the diversity of appliances presented in household environments and the spread spectral of harmonic insertion of CLF Lamps that are the major harmonic generator in a household environment (up to 84%). This differs from workplace environments, that typically have the majority of harmonic insertion generated by desktops and lighting. And once the lighting is majorly provided by ballast lamps with low harmonic insertion, its greater contributor are desktops representing 74%, whereas lighting represents 20% of total harmonic generation.

A complete display of household and workplace environments harmonic components influence for low, average and high consumption scenarios is presented in Table VI.

TABLE VI. HOUSEHOLD AND WORK ENVIRONMENT HARMONIC COMPONENTS INFLUENCE

		Harmonics Component Influence												
Environment Scenario		*3rd*	*5th*	*7th*	*9th*	*11th*	*13th*	*15th*	*17th*	*19th*	*21th*	*23th*	*25th*	*27th*
Household	*Low*	26%	18%	13%	10%	7%	5%	4%	3%	3%	3%	3%	3%	3%
	Average	***26%***	***18%***	***14%***	***10%***	***6%***	***4%***	***4%***	***3%***	***3%***	***3%***	***3%***	***3%***	***3%***
	High	27%	17%	12%	10%	7%	5%	4%	3%	3%	3%	3%	3%	3%
Workplace	*Low*	35%	11%	9%	9%	8%	7%	5%	6%	3%	3%	1%	1%	1%
	Average	**35%**	**11%**	**9%**	**9%**	**8%**	**7%**	**5%**	**6%**	**3%**	**3%**	**1%**	**1%**	**1%**
	High	38%	10%	7%	9%	9%	7%	5%	6%	3%	3%	1%	2%	2%

To better observe the difference between the harmonic generation in household and workplace environments, the average consumption scenarios are illustrated in Fig. 9.

It is clearly observable that work environment harmonic injections are majorly caused by 3rd harmonic component in face of household environments that presents a more distributed harmonic injection between its components, although it is also majorly inducted by 3rd harmonic component.

As earlier described, this situation is due to the major contributors in both environments, CLF lamps in households and Desktops in workplaces, that are responsible for more than 70% of the environment harmonic generation in all energy consumption scenarios. This makes their environments' harmonic generation be very similar to their own harmonic profiles.

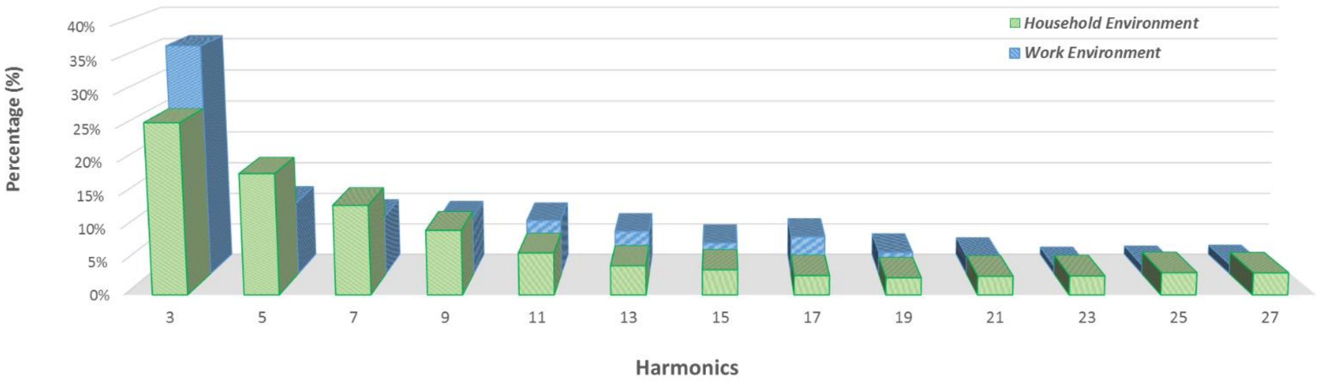


Fig. 9: Comparison between harmonic components influence in household and workplace environments for the average energy consumption scenario

VI. Conclusion

This paper used real data and measurements to perform the environment modeling of harmonic loads under different utilization rates. The results provided meaningful information in determining the impact of the environments on the generation of harmonics; the harmonic components and equipment influence on the harmonic injection; and the differences and similarities of the analyzed contexts from the perspective of harmonic generation. Finally, the results indicated that with just two aspects, load environment and usage pattern, a good representation of the distortion profile may be provided without the need of a complex modeling.

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