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Remy Rigo-Mariani, R. K Rayudu, M. S Witherden. Effect of multiple compact fluorescent lamp usage on residential power quality. 2012 IEEE International Conference on Power System Technology (POWERCON 2012), Oct 2012, Auckland, France. pp.1-6, 10.1109/PowerCon.2012.6401250 . hal-03519974

HAL Id: hal-03519974

<https://hal.science/hal-03519974>

Submitted on 10 Jan 2022

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Effect of Multiple Compact Fluorescent Lamp Usage on Residential Power Quality

R. K. Rayudu, *Senior Member, IEEE*, R. Rigo-Mariani and M. S. Witherden

Abstract—This paper discusses the results of experiments performed to analyze the effects of multiple compact fluorescent lamp usage on residential power quality. CFLs are quickly replacing incandescent lamps in home lighting but their effects as non-linear loads on residential power quality is unknown. We performed 15 sets of experiments with different CFLs and analyzed their harmonic interactions. The results provided interesting outcomes in terms of collective contribution and harmonic cancellation. Some of the results are tabulated in this paper and discussed.

Index Terms—Harmonic Analysis; Power Quality; Energy efficiency; New Zealand Studies; Residential Power Quality; CFLs

I. INTRODUCTION

THIS document discusses the effect of multiple compact fluorescent lamps (CFLs) usage on residential power quality. CFLs are fast replacing regular incandescent lamps at homes. However, like any non-linear load, CFLs inject severe harmonic currents into the grid [1, 4-13, 16]. CFLs have been extensively researched and several models have been analyzed [16]. However many studies have been performed at distribution network level and there is a need to understand the power quality issues at the residential level. The primary aim of this research is to collect residential power quality data associated with the use of typical non-linear loads.

One of our activities towards our research goal is to gather power quality data related to residential CFLs that are readily available in the local market. We have conducted several experiments and our initial results were published in [1]. Of the CFLs we tested, we could clearly classify them into Low Performance (LP) and High Performance (HP) lamps. LP lamps harmonic indices were worse and many lamps failed part A of AS/NZS 61000-3-2 (2003) for class D equipment.

This paper extends our discussion in [1] to discuss the

harmonic interactions of CFLs used at the same time. Section II discusses the harmonic indices of multiple CFLs in operation and the details of our experiments. In Section III we present and discuss the results. Our findings are concluded in the section IV.

II. HARMONIC INDICES OF MULTI CFLS

In our previous publication [1], we discussed harmonics generated by individual CFLs. As an extension of our research, our intention is to investigate the harmonic interactions between multiple CFLs. Several investigations report that an average household uses around 2-5 CFLs at any single instances [2, 3]. Hence, in this study we report the harmonic indices interaction between 2 to 5 CFLs.

Since the network is radial downstream to the PCC, harmonic levels observed at a node correspond to the interaction of harmonics injected by all the operating nonlinear devices. They affect the voltage waveform and therefore all the loads fed down the node. However it is difficult to estimate the exact impact on the grid of a single non-linear load.

One of the problems with harmonics is that the contributions from different non-linear loads cannot simply be added algebraically. Each order harmonic is characterized by a magnitude and a phase angle. This angle corresponds to the phase between harmonic current and harmonic voltage at the same frequency. It could also be associated with the phase shift with the reference sinusoidal fundamental signal. Obviously angles attached to different loads are not always the same. Thus the overall magnitude for a harmonic will be less or equal to the sum of all the magnitudes.

The vector sum of harmonics from two different loads at same order is given by:

$$\begin{aligned} &= I_{1n} \sin(m\omega t + \Phi_{1n}) + I_{2n} \sin(m\omega t + \Phi_{2n}) \\ &= (I_{1n} \cos \Phi_{1n} + I_{2n} \cos \Phi_{2n}) \sin(m\omega t) + (I_{1n} \sin \Phi_{1n} + I_{2n} \sin \Phi_{2n}) \cos(m\omega t) \\ &= A \sin(m\omega t) + B \cos(m\omega t) \end{aligned}$$

and their magnitude is given by

$$\begin{aligned} &= \sqrt{A^2 + B^2} \\ &= \sqrt{(I_{1n} + I_{2n})^2 + 2I_{1n}I_{2n}(\cos(\Phi_{1n} - \Phi_{2n}) - 1)} \end{aligned}$$

A. Experiments

In this set of experiments to analyze the harmonic interaction effects of CFLs, between 2 to 5 CFLs were plugged in at the same time and their power quality characteristics measured. The purpose was to see how characteristics of a lamp can be affected by harmonic currents coming from other

This work was supported in part by Massey University Research Fund under Grant 08/0156. A few of the lamps tested were donated by EECA, Philips and Osram.

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local non-linear loads (including CFLs).

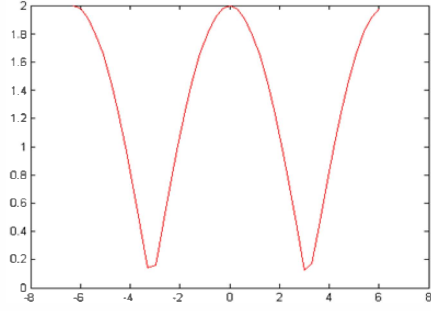


Fig. 1. Harmonic Magnitude vs difference between angles (rads).

Compared to single CFL analysis [1], power consumed and Irms input current may also vary from the former values due to the voltage variation. At the same time, the experiments illustrate how harmonics interact. Individual results from [1] are compared with characteristics of the combined CFL load in these experiments. Special attention is paid to the difference between the sum of all the magnitudes and the overall magnitude for each harmonic. At each order the difference is calculated:

$$err_h(\%) = \frac{\sum I_h - I_{hmes}}{I_{mes}} \times 100$$

Then the average value of the difference is determined. In most cases, only the first thirteen orders were considered for simplicity. Indeed, for high orders, measurements become less accurate due to the presence of noise.

TDHv(%) was also calculated for each case, before and after plugging in the lamps. As the distortion of the supplied voltage keeps changing, the change in percent of the TDHv has also to be considered.

At the time of performing these experiments only one Power Quality Meter was available, so the only measurable power is the one for the overall load. In this analysis of the results for characteristics, attention was given to the input current, the THDi and the K-Factor.

Fifteen experiments were carried out outlining different combinations of both Low Performance (LP) lamps and High Performance (HP) lamps discussed in [1]. Both low and high performances products were combined.

III. RESULTS

A. Two LP lamps

The LP lamp 1 and LP lamp 2 were plugged in at the same time. The following figure (Fig.2) shows the current waveforms comparison of combination effect versus the individual lamps. The peaks of the current waveforms of the combination of lamps are a little lower and delayed compared to the individual lamp waveform (black line).

Judging from the waveforms it appears that the performances have fared better compared to individual lamps. A further analysis is carried out by calculating harmonic indices for the two lamps. The table below show the differences in the values obtained with the combination.

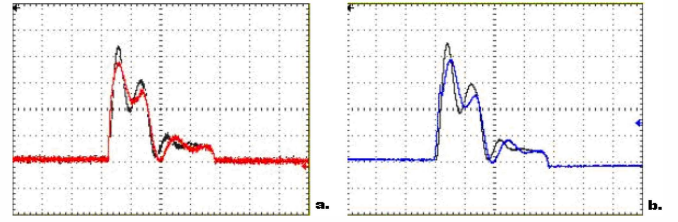


Fig. 2. Current waveforms 100mA, 1ms

TABLE I
HARMONIC INDICES OF TWO LP LAMPS

	LP Lamp1		LP Lamp2	
	on its own	with LP Lamp2	on its own	with LP Lamp 1
Irms	101mA	108mA	101mA	99.5mA
PF	0.53	0.51	0.58	0.57
THDi	132.8%	145.25%	133.1%	118.79%
K-Factor	97.6	52.98	85.31	44.65

	LP Lamp1	LP Lamp2	Combined Load
Power	13.5W	13.8W	27.3W
Irms	108mA	99.5mA	199mA
PF	0.51	0.56	0.57
THDi	145.25%	118.79%	128.15%
K-Factor	52.98	44.65	46.91

It is noticeable that the combined THDi and Power Factor are better than the ones observed individually for the lamps. This is a direct effect caused by the cancellation of harmonics with different phase angles. We can visualize that phenomenon by displaying the spectrum analysis with the calculated sum of the individual harmonic magnitudes (Isum) and the measured individual harmonic magnitudes (Imes) of the combined load (Fig. 3).

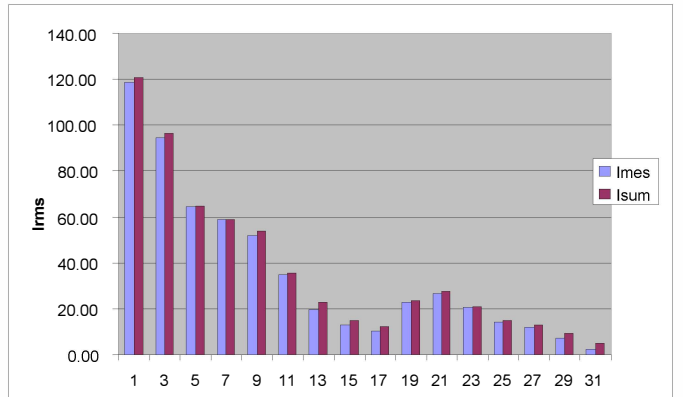


Fig. 3. FFT sum and measured combined load of two LP lamps

As expected, magnitudes corresponding to harmonics of the overall load were always lower than the sum of the individual

magnitudes. For all the 29 orders considered, the average value of the difference is 7.38%. If we consider only the first thirteen orders the difference drops off to only 3.65%. The low difference could be explained by the fact that ballasts are similar. Therefore phase angles associated to the harmonics currents are close together; at least from the first harmonic to the thirteenth.

When the experiment was carried out, the THDv calculated with no load was 2.66%. THDv calculated after plugging in the bulbs was equal to 2.72% which represents an increment of 2.2%.

B. Combination of one LP and HP Lamp

This section discusses the harmonic indices of combining a LP lamp with a HP lamp. Like in the previous case a mere glance at the current waveforms reveal some variations.

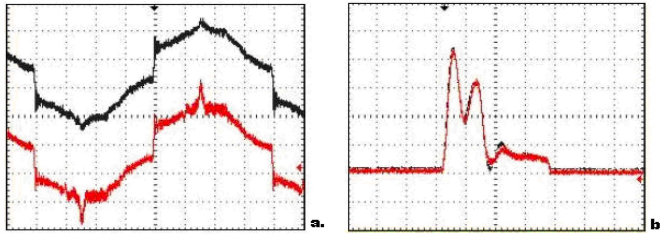


Fig. 4. Waveforms of HP lamp current (a - 50mA, 5ms) and LP Lamp1 (b - 100mA, 1ms)

Differences are less noticeable for the LP lamp. Just one of the two peaks reduced but much less than in the previous experiment discussed in section A. It appears that the current of the LP lamp1 was much less affected by the HP lamp than it was with the LP lamp2. From the Figure 4, it is evident that the LP lamp affected the waveform of the HP lamp as it became distorted, with observable peaks.

TABLE II
HARMONIC INDICES OF COMBINING A HP & A LP LAMP

	HP Lamp 1		LP Lamp 1	
	on its own	with LP Lamp 1	on its own	with HP Lamp 1
Irms	59.2mA	56.4mA	101mA	99.6mA
PF	0.95	0.94	0.53	0.56
THDi	13.53%	18.12%	132.8%	126.85%
K-Factor	2.94	4.83	97.6	85.66

	HP Lamp1	LP Lamp1	Combined Load
Power	12.8W	13.2W	26.0W
Irms	56.4mA	99.6mA	143mA
PF	0.94	0.56	0.76
THDi	18.12%	126.85%	70.51%
K-Factor	4.83	85.60	38.66

Judging from the table above, with this combination of an LP and an HP lamp, performance of the LP lamp increased

while the performance of the HP lamp worsened. But characteristics do not change in the same proportions.

For the overall load, the current appears to be really distorted as the peak for the LP lamp occurs when the current of the LP lamp reaches its maximum value (Figure 5).

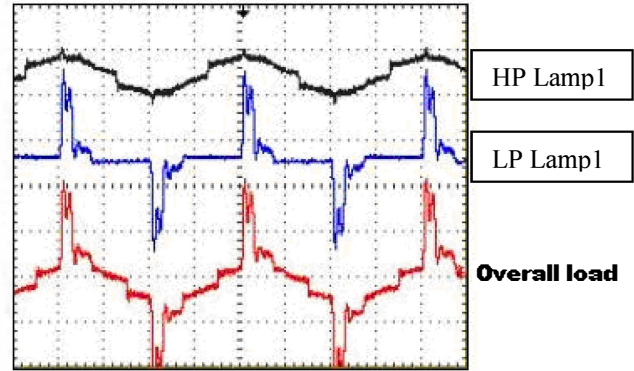


Fig. 5 Individual and overall currents - 200mA, 5ms

Performances of the overall load are within the specifications related to the two lamps. But harmonics indices were far away from the ideal value observed for the HP lamp with the Power Factor becoming less than 0.8.

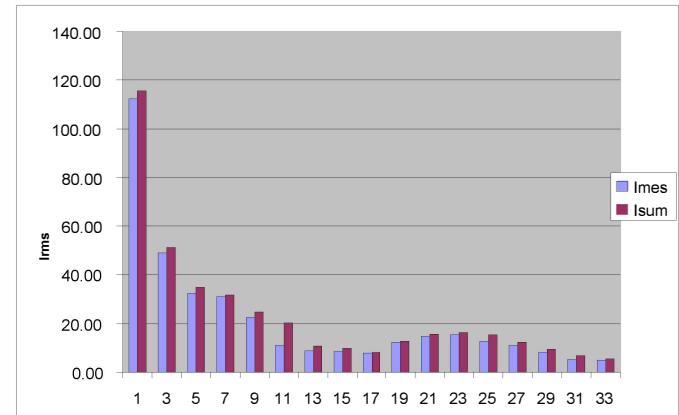


Fig. 6. FFT sum and measured combined load of combined load (Exp2)

As with the combination of two LP lamps, the sum of harmonic magnitudes is close to the overall magnitude for each order. The average change to the thirteenth order is equal to 18.18%. It is higher than the change calculated in the previous experiment (Section A) because of the ballast differences between the LP lamp 2 and the HP lamp. The two electronic ballasts do not generate the same current and thus the difference between phase angles is more significant.

THDv increase was about 1.55%; from 2.58% to 2.62%. Compared to the previous experiment, the presence of the HP lamp in the circuit limited the voltage distortion. The increase was less than with two LP lamps used.

C. Combination of two HP Lamps

This experiment was conducted by using two HP lamps. As expected, with the combination, the overall current remained close to a proper sine wave. Thus performances of the overall

load are obviously good, and even better than individual HP lamp usage (Figure 7) with a measured Power Factor up to 0.97, THDi equal to 13.04% and K-Factor of only 2.55.

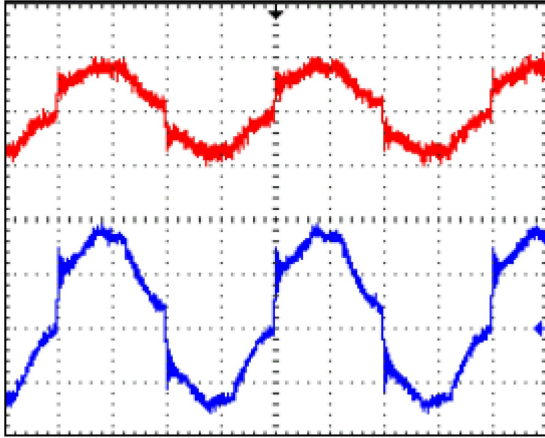


Fig. 7. Individual (Red) and overall (Blue) current- 100mA, 5ms

With regards to individual characteristics, we even noticed improvements of the two lamp combination compared to individual lamps: THDi of 13.28% instead of 19.3% and power factor of 0.94 instead of 0.91.

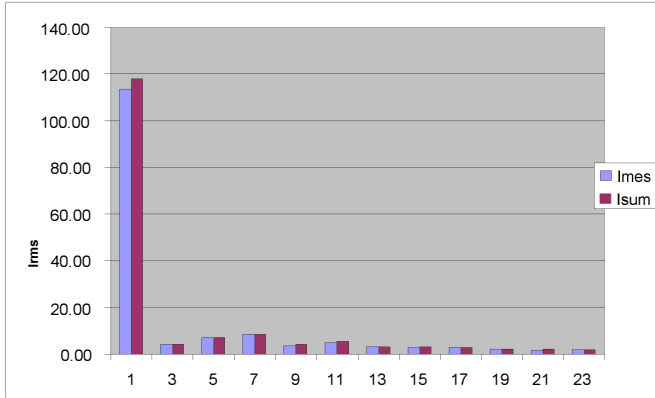


Fig. 8: FFT sum and overall load (Exp3)

The average difference between the sum of the magnitudes and the overall magnitude was 6% taking all the orders into account. It drops off to 4.99% for thirteenth first orders. The THDv associated to the load is equal to 2.68% instead of 2.66% with no load which only represents an increment of 0.7%.

D. Multi combination Lamp Results

This section discusses the results obtained by testing two to five bulbs at the same time. After analyzing the interaction effects of two CFLs, we performed additional experiments by adding further CFLs to the combination.

As the CFLs are connected in parallel, the overall current is the sum of the individual currents. With all LP lamps connected, the overall current presents the same distortion as the individual lamp waveforms. Figure 9 shows the waveforms of both individual lamps (a) and the combination waveform of five LP lamps (b). The peaks occur at the same time and have almost the same shape.

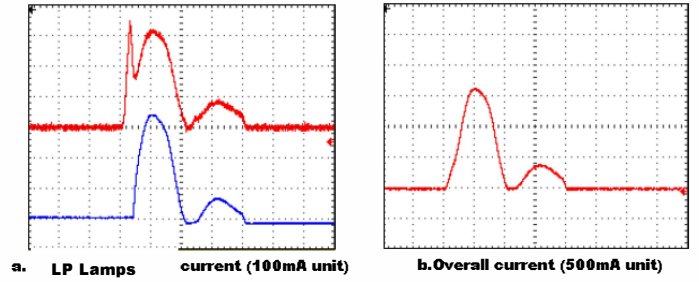


Fig. 9. Individual and Overall Currents

Obviously when only the HP lamps are combined together the overall current remains almost sinusoidal. When LP and HP lamps are used in combination the total current displays peaks whose magnitude depends on the ratio of the number of HP and LP lamps. Figure 10 shows the waveforms for four lamps; (a) One HP and 3 LP lamps and (b) 3 HP and one LP lamps.

Peaks associated with LP lamps occur when the sinusoidal signal for HP lamps reaches their maximum value. As the magnitude of the peaks from the LP lamps are greater than the magnitude of the peaks from the LP lamps, the ratio of HP to LP lamps is important to obtain a cleaner signal (over 60% of the lamps need to be HP) as the magnitude of the peaks from the LP lamps are three to four times greater than the magnitude of the peaks from the LP lamps.

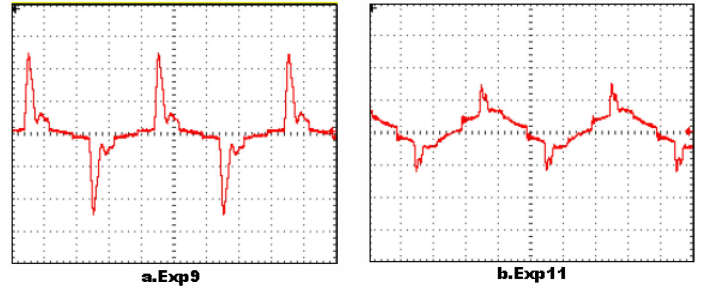


Fig. 10. Overall current - 500mA, 5ms

The following table (III) illustrates the power factor dependencies between combination of LP and HP lamps.

TABLE III
POWER FACTOR OF COMBINING SEVERAL HP & LP LAMPS

Number of lamps	Only LP Lamps	Include one HP Lamps	Include two HP Lamps	Include three HP Lamps	Only HP Lamps
1	0.55	-----	-----	-----	0.91
2	0.57	0.76	-----	-----	0.97
3	0.59	0.72	0.88	-----	0.97
4	0.56	0.66	0.78	0.90	-----
5	0.57	0.64	0.76	0.85	-----

The Power Factor measured was, in most of the cases, below the acceptable value for HP Lamps. For loads that were composed by high performance lamps there is no problem. But the Power Factor decreases dramatically when a number of low performance lamps are included. Judging from the table

above, the Power Factor becomes low when the ratio of HP lamps over total number of load is less than three quarters. In our experiment with three HP lamps and one LP lamp, the RMS current associated with the HP lamp represent 61% of the overall current.

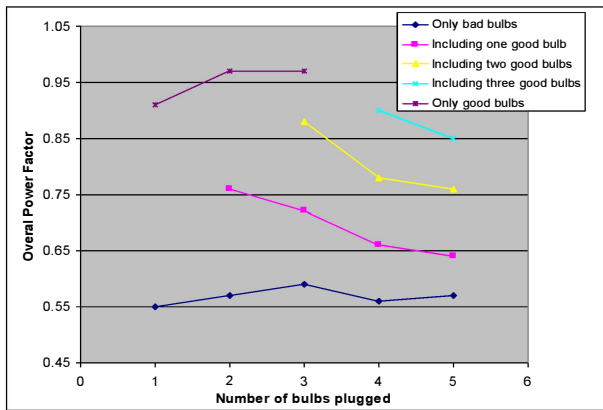


Fig. 11. Changes in Power Factor with Lamp combination.

The THDi decreases and reaches better values when the numbers of HP lamps are higher in the combination. But at the same time it is interesting to note that it does not worsen so much with the number of LP lamps (Table IV column 1). The THDi observed for five low performances lamps together is even better than the one for four LP lamp combinations. Due to the harmonic cancellation, the overall THDi remains in the range defined by the associated loads.

TABLE IV
THDi (%) OF COMBINING SEVERAL HP & LP LAMPS

Number of lamps	Only LP Lamps	With one HP lamp	With two HP lamps	With three HP lamps	Only HP Lamps
1	132.80%	-----	-----	-----	19.3%
2	128.15%	70.51%	-----	-----	13.04%
3	119.45%	85.82%	47.75%	-----	12.95%
4	134.06%	100.00%	72.26%	38.79%	-----
5	126.47%	100.50%	79.68%	55.49%	-----

K-Factor obviously decreases when more high performance lamps were used in combination. At the same time, interestingly, the characteristic becomes better when the number of LP lamps increase from 1 to 5 (Table V). But then the improvement caused by adding a LP lamp is lower than adding a HP lamp. In general, K-Factor decreases with the number of added lamps. But it is still considerably high especially if only LP lamps were considered. Values below IEC (AS/NZS) 61000-3-2 standards were observed only for the loads with HP lamps.

TABLE V
K FACTOR OF COMBINING SEVERAL HP & LP LAMPS

Number of lamps	Only LP Lamps	With one HP lamp	With two HP lamps	With three HP lamps	Only HP Lamps
1	97.60	-----	-----	-----	4.83
2	46.91	38.66	-----	-----	2.55
3	32.13	32.92	26.95	-----	3.07
4	32.92	29.42	36.5	17.30	-----
5	27.49	27.99	25.22	13.60	-----

Another important factor to evaluate the overall load is the effect of THDv. For each case, the difference between the THDv without and with the other loads was calculated. Results obtained are analogous to observations previously made about the harmonic indices.

TABLE VI
THDv OF COMBINING SEVERAL HP & LP LAMPS

Number of lamps	Only LP lamps	With one HP lamp	With two HP lamps	With three HP lamps
1	+1.64%	-----	-----	-----
2	+2.23%	+1.55%	-----	-----
3	+4.63%	3.44%	+1.43%	-----
4	+11.60%	+6.46%	+5.79%	4.79%
5	+22.85%	+16.07%	+12.54%	10.9%

THDv increases dramatically with the number of low performance lamps. It reaches almost 23% for five LP CFLs in the circuit. Analyzing the spectrum of the voltage, we noticed that using LP lamps leads to a reduction of the 5th harmonic while all the others increased. The fundamental still remained at the value of 234.98V. The highest THDv observed corresponds to the highest increase and was equal to 3.44% (Experiment 12 with five LP lamps). Including high performance lamps in the circuit noticeably reduced the effect of LP lamps on the voltage distortion.

When only HP lamps are plugged in there was almost no effect on the voltage distortion as the levels of harmonic currents remained low. Changes recorded were equal to only 0.7% for two HP lamps and 1.55% for three.

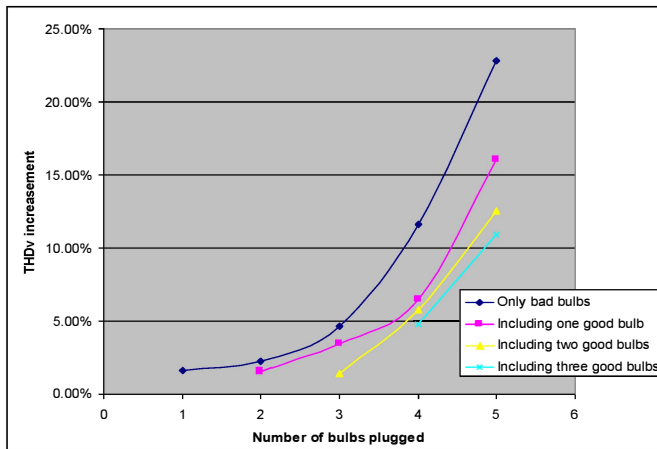


Fig. 12. THDv in % for the load combinations.

IV. DISCUSSION

Compact fluorescent lamps are quickly replacing incandescent lamps worldwide. With multiple non-linear loads replacing linear loads, residential power quality is becoming an issue. To analyze the effect of CFLs on power quality, we tested several CFLs readily available in the market and our initial results were published in [1]. This paper extends our observations and discusses the effects of using multiple CFLs.

Our initial results [1] classified the lamps into low performance (LP) and high performance (HP) lamps. In this set of experiments we combined the lamps to analyze their combined effects on overall harmonic indices. The tests were conducted using a combination of 2 to 5 lamps. The current waveforms and the power factor were worse when all LP lamps were used. However many factors such as THDi and power factor, fared better with combined loads than individual loads, indicating harmonic cancellation. LP lamps with similar ballasts fared better when switched on at the same time although never close to IEC (AS/NZS) standards.

An inclusion of at least one HP lamp provided better harmonic indices. The only exception is the K factor where the effect is significant with 3 HP lamps out of a total five lamps. Our results indicate that the HP lamp ratio should be over 60% of the total CFLs in a residence to maintain high power quality.

We have developed generic models of the CFLs studies are underway on the effect of multi CFLs on the power network. Also we are currently performing phase dependency analysis and their interaction.

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