Power Quality Indices of Compact Fluorescent Lamps for Residential Use – A New Zealand Study

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***Abstract*—This paper discusses the power quality indices of Compact Fluorescent Lamps (CFLs) used in residential lighting. Harmonic indices are important factors when analyzing residential power quality. Research carried out in the recent past has highlighted power quality issues relating to CFLs. The experiments performed by us confirmed the stated issues. Most brands tested had low power factor associated with high harmonic current levels. A few high power factor products with low harmonic current levels also exist and were highlighted in this research.**

I. Introduction

With the increasing number of non linear residential loads in New Zealand, understanding and analyzing Power Quality issues has become a real challenge. All these new devices, which are characterized by high electronic component counts, inject severe harmonic currents into the grid. These harmonics go upstream within the network and affect the voltage waveform, which may become very distorted, deviating far from a proper sinusoidal signal [2, 10].

Among the non-linear loads used in household, Compact Fluorescent Lamps (CFLs) have been discussed for years now. With lower power consumption and longer lifespan, these products are expected to replace the incandescent bulbs. Today such lamps are available with self integrated ballasts which enable their correct operation. The problem is that their current is severely distorted and contains high harmonic content. Thus most CFLs appear to be characterized by the low power factor associated with this high THDi(%) and wide use of them may led to severe drop in the power quality of the New Zealand Residential Power Network (Grid).

The primary objective of the research is to gather residential power quality data associated with typical non-linear loads. An initial step was to analyze the non-linear loads individually. We chose household CFLs for this analysis. The CFLs were tested and their harmonics indices measured to observe their compliance with international requirements. To be as neutral as possible, lamps studied came from the brands widely available to the consumer from local retail outlets. In this paper, the lamps were only judged with regards to their power quality issues and more specifically the harmonic currents they generated.

Characteristics such as luminosity, interference and lifetime were not considered. Results obtained were used to classify the lamps depending on their performances.

This paper is organized as follows: Section II discusses CFLs and their characteristics. This is followed by a discussion on present international standards and research into CFL power quality. Section III discusses our selection of harmonic indices. Each lamp's harmonic indices are then discussed in section IV.

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II. Compact Fluorescent Lamps (CFLs)

CFLs were introduced into the market in the 80s and were expected to replace less efficient incandescent lamps. With electromagnetic ballasts, they quickly became widely used in commercial and industrial areas. Yet it was difficult for them to penetrate in the residential areas, mainly because of the quality of the light produced, their bulky size and their high price. Over the years, products have improved while an increase in production volumes (and to some extent, subsidies from several governments) made their price affordable. Since electronic ballasts have been introduced, the consumer could directly plug the lamps in place of incandescent ones [4].

A. Pros and Cons of CFLs

CFLs are claimed to provide more advantages when compared to a basic incandescent bulbs. Firstly, they use 20% to 25% of the power consumed by an equivalent light output, traditional, incandescent lamp. This obviously represents great savings in both energy costs and the preservation of natural resources. Such performances provide benefits for utilities which are often looking for ways to reduce connected load or for strategies that can help slow the rise in overall demand. The average rated life of a CFL is claimed to be between 8 and 15 times that of incandescent [4, 13, 16]. CFLs typically have a rated lifespan of between 6,000 and 15,000 hours, whereas incandescent lamps are usually manufactured to have a lifespan of 750 hours or 1,000 hours [4].

On the other hand, a great number of problems are linked to CFLs: recycling, interferences with telecommunication or other equipment, high mercury levels, fire hazard, etc. [5].

The main scope of this paper is the analysis of harmonic currents injected into the grid by CFLs. Indeed these products, and especially lamps with integrated electronic ballast, are characterized by very high harmonic distortion which leads, among other things, to a low Power Factor.

Unlike incandescent bulbs which have sinusoidal current waveforms, CFLs have a distorted current waveform. Despite their advantages; reduced lamp flicker, quieter operation, etc., electronic ballasts have led to higher distortion than magnetic ballasts. The role of such ballasts is to adapt the power consumed by the lamp, regulating the discharge voltage and current [6].

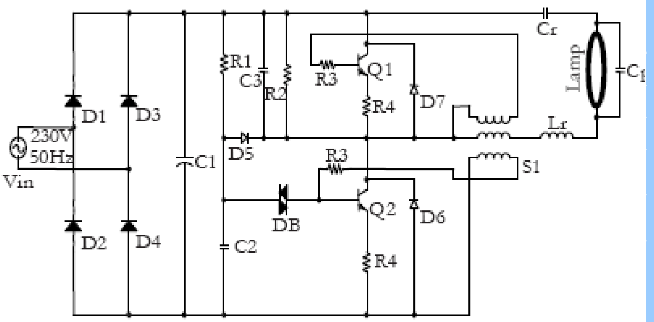

Fig 1: Schematic for a general low cost ballasts [6].

The single phase voltage 230V, 50 Hz is converted into DC by the Diode Bridge and capacitor C1 as shown in Figure 1 above. Then self-oscillating signals are generated by the two transistors in alternative sequence via a transformer.

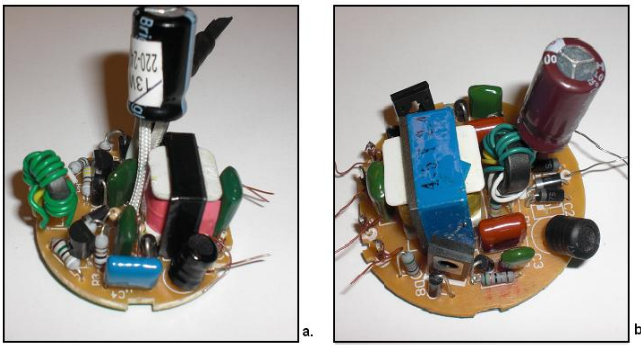

Fig 2: Ballasts of Lamp 1 (a) and Lamp5 (b) from Table II.

B. International Standards

Just like any non linear load, CFLs must comply with international standards relating to harmonic levels. In addition they have to conform with other special specifications such as light intensity, lifespan, etc. [3, 5, and 7].

With regards to harmonic content, the latest Australian/New Zealand standards (AS/NZ 61000.3.2:2003) are directly derived from IEC 61000.3.2 [3]. CFL bulbs are identified as class C lighting equipment. However, a clause in the standard states that class C equipment with input power of less than or equal to 25W must instead comply with the requirements of class D. In particular it specifies that discharge lighting equipment, having an active input power of less than or equal to 25 W, shall comply with one of the following sets of requirements:

- Harmonic currents shall not exceed the power-related limits advised on the table for Class D equipments **or**
- The third harmonic current, expressed as a percentage of the fundamental current, shall not exceed 86% and the fifth shall not exceed 61%: moreover, the waveform of the input current shall be such that it begins to flow before or at 60°, has its last peak (if there are several peaks per half period) before or at 65° and does not stop flowing before 90°, where the zero crossing of the fundamental supply voltage is assumed to be at 0°.

TABLE I
HARMONICS LIMITS FOR CLASS D EQUIPMENT [3]

Harmonic Order N	**Maximum permissible harmonic current (mA/W)**	**Maximum permissible harmonic current (A)**
3	3.4	2.3
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13<n<39 odd harmonic only	$\frac{3.85}{n}$	$\frac{2.25}{n}$

Other international standards establish similar limits as shown in the table above. In other international standards Crest Factor is suggested to be less than or equal to 1.7; THDi less than 32%; and power factor greater than 0.9. The K-Factor for such electric discharge lighting is expected to be around 4. In this report all the CFLs will be judged regarding all these values and characteristics. [8, 9].

Since this research was completed, and as a direct result of this research, a "New Zealand Only" clause has been added to AS/NZ 61000-3-2:2003 in order to improve the standard for New Zealand by effectively removing the second bullet point requirement.

C. Existing Research

There has been some research in the recent past to estimate the impact of CFLs on the grid with regards to voltage distortion caused by harmonic currents. Outputs are commonly based on impact measurements on the network, simulations or just extrapolations straight from CFLs characteristics. It's important to note, however, that results varied a lot.

The earliest studies often concluded that even if each CFL is a low power device, a combination of several devices would causes unacceptable voltage distortion [10, 14]. Computer modelling of the grid, by mixing all types of residential loads, has shown that the voltage distortion varies considerably at various nodes in the feeder. The simulation was based on the worst case, that is to say by adding the harmonic magnitudes of each device. The location and size of capacitors banks in particular had strong effects on the results. Modelling showed that on 56% of the nodes, THD*v* was over 5% and even reaches values greater than 15% with resonance or near resonance conditions [10, 14].

A simulation for a distribution company in the Melbourne area [14] showed that due to the low share of lighting in peak demand (20% in Australia), the reduction of energy consumption would not be so significant with the expansion of CFLs in households: only 0.8% energy saving for 20% usage and 1.8% for 40% usage corresponding to a reduction of 8% of the domestic peak consumption. At the same time THD*v* is expected to be over 10% for a larger CFL usage [14].

A New Zealand study was aimed at estimating the maximum number of CFLs per household required to surpass the THD limit of 5%. Widely available CFLs were assumed to be installed. A model of the New Zealand's South Island 220 kV grid was used, from the 220 kV bus at Islington to the customer switchboard. The study results indicated that the THD at the PCC reached 5% at a load of 920 CFLs of 20W, or at 14 lamps per household [15].

Contrary to this, many other studies, both old and recent, concluded that there would not be any problem caused by the penetration of CFLs on the grid. Measurements carried out in Swedish households and the network has proved that harmonics from CFLs constitute a very small part of total harmonic current in the grid. A high degree of penetration would correspond to 100W per household which is lower or equivalent to a PC modem or a TV. The worst case harmonics will be approximately 800ma and there is no evidence that it could become problematic. Besides, it has been observed that installing many CFLs could result in reduction in voltage distortion depending on the cancellation of harmonics [16].

It is surprising to see by how much results can vary from one research to another. In fact we could legitimately wonder if some of those surveys are truly neutral, or if other factors such as particular countries grid impedance may be affecting the results. In any case, it is obvious that the impact of CFLs on power quality has not been completely explained and there are still many unknowns. This leads to a kind of misunderstanding; For example, while governments encourage the usage of such lighting, some facilities have chosen not to use it- examples being Lund University Hospital in Sweden and Lincoln University, New Zealand [15].

There is one point on which most of the surveys agree: the lack of information for consumers and above all the lack of international standards or test protocols. Thus we cannot trust the specifications given by manufacturers. Results also vary a lot with testing conditions and the age of bulbs. For instance it has been proved that even power factor correction circuit became less efficient when they are older but that kind of information is not likely to be provided by manufacturers. All these misunderstandings have led to the creation of organizations such as *International CFL Harmonization Initiative (2006)* which aims at developing international standards and finally provided high-quality lamps [22].

III. Harmonic Indices of Residential CFLs

The CFLs tested in this research all have integrated electronic ballasts. These models are the ones which could easily replace incandescent bulbs as they have the same bases, screw or bayonet. To be as neutral as possible the lamps studied came from local supermarkets. All the brands widely available to the consumers were used. The power consumed by each model is around 15W which is supposed to be roughly equivalent to a 75W incandescent bulb.

The lamps were tested individually to avoid problems due to harmonics injected by other loads which might affect results. Their characteristics were calculated: I*rms*, V*rms*, Power, I*peak* and harmonic current magnitude as inputs, THD*i*, PF, DPF, Distortion Power, Crest Factor and K-factor as outputs. Attention was paid to their compliance with standards and other criteria. CFLs were left switch on for at least 15min before processing measurements. Here below, is a list of the models tested with values of Power and I*rms* given by manufacturers.

TABLEII
Models of CFLs used

Model	Power	Current Input
1	13W	115mA
2	14W	116mA
3	14W	116mA
4	15W	
5	15W	110mA
6	14W	100mA
7	15W	
8	13W	60mA
9	15W	57mA

IV. Results and Analysis

First of all, an obvious and significant discovery is the difference between high performance products and the others. It is not our intention to identify the high performance lamps but the fact is that they belong to one brand and their CFLs comply perfectly with standards whereas all the other lamps presented highly distorted current waveforms corresponding with greater harmonics. That led us to comment about the results in two different parts: low performances (LP) products and high performance (HP) lamps.

Lamps 1 to 7 were identified as low performance lamps and only lamps 8 and 9 were high performance lamps.

A. Low Performance Lamps (Lamps 1-7)

1) Waveforms and Crest Factor

A mere glance at the current waveforms is enough to make us realize how important harmonics are. All the current waveforms are very peaky and highly distorted. It is interesting to notice that they are quite similar with a main peak directly followed by a smaller one.

With all these similarities we could wonder whether the ballasts come from the same manufacturer. For the low performances bulbs, only Lamp 3 differs from the others with a main first peak. All the others appear to be really close.

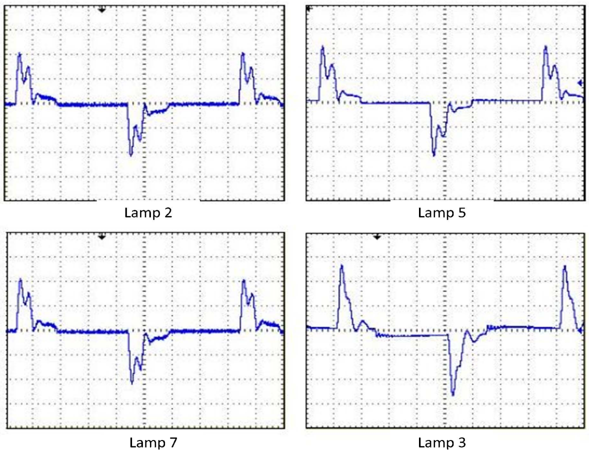

Fig 3: Current Waveforms- 200mA, 2.5ms

The peaky currents are of course associated with high crest-factors (CF). CF is greater than 3 for all the LP bulbs and even reaches 4.2 for lamp 1.

2) THDi, Distortion Power and Power Factor

THD*i* average value is 123%. Maximum values of 132% and 133% were obtained for lamp 6 and lamp 1. Results were far away from some standards that recommend THDi to be less than or equal to 32%. By definition there was more energy contained in the harmonics than in the fundamental (See table III). We can infer the same conclusions by comparing the Power (W) with the Distortion Power (VAd). Indeed in many cases the Distortion Power was over 20VAd whereas the active is around 15W.

The average Apparent Power Factor for all these products is 0.55. Values were considerably below some international recommendations. The lowest values correspond to the lamps 2 & 3 (0.53) and none of the CFLs were over 0.6. The highest value was 0.59 for lamp 4.

On the other hand the measured DPF remain high, with values around 0.9. This comes from the fact that most of the active power consumed is carried in the fundamental frequency at which we observed a phase shift between voltage and current equal to approximately 20°.

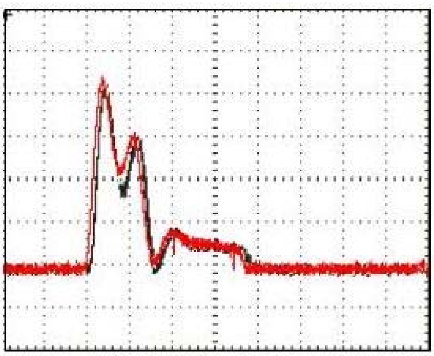

Fig 4: Superimposition of the currents for Lamps 7, 5 and 3- 100mA, 1.0ms

3) K-Factor

In most cases, the calculated K-Factor was over typical international recommendations, that is to say greater than 40. It reached 92 for the lamp 6.

4) Power Consumption and Irms

Power and I*rms* are more or less close to the specifications given by manufacturers. In most cases, the current is a little higher: for example, 118mA instead of 110mA for the lamp 5. For lamp 1, the I*rms* measured is even lower; 101mA instead of 115mA. With regards to the Power, the average discrepancy with specified values is 1.6W. Sometimes the Power measured is more; 16.5W against 15W for lamp 5; and sometimes less; 11.7W against 14W for lamp 4. Differences between measurements and manufacturers information could be explained by the conditions of the experiments and obviously different from the ones used by companies. The switch-on time before measurements, the age of the bulb, the circuit used, and even the ambient temperature can also contribute to these errors. Manufacturers are generally also only required to state "nominal" values, so this could also account for these variations.

5) Standards Compliance

All the harmonic indices for low performances CFLs were well over the first bullet point limits in the international standards. By using spectrum decomposition, it was possible to compare harmonic currents against the IEC requirements, first bullet point which refers to Table I.

Limits are expressed in mA/W for each harmonic. Thus the limit values have to be calculated for each lamp depending on its power. The following graphs show how the lamps fared against Table I.

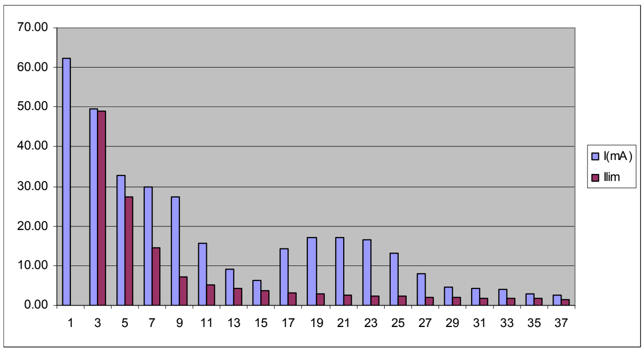

Fig 5: FFT and comparison with the standards for the Lamp 1.

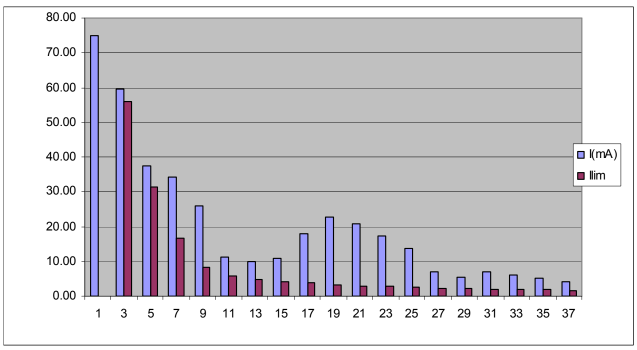

Fig 6: FFT and comparison with the standards for the Lamp 5.

Even the 3rd and 5th harmonics do not comply with the limits of Table 1 in terms of percent of the fundamental as discussed in Section B. But the low performance lamps may comply with the second alternate requirement of the standard as the current does not stops flowing before 90° crossing for the voltage (Fig. 7).

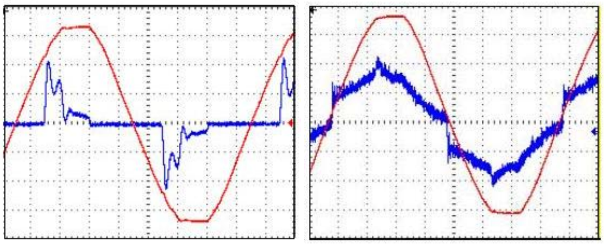

Fig 7: Voltage and current waveforms of Low (left) and High (Right) performance Lamps- 50V, 200mA, 2.5ms

B. High Performance Lamps

The tested high performance lamps had the following characteristics: a twist shaped; 15W, 57mA; and a bayonet; 13W, 60mA. Current waveforms associated with these lamps were very close to sinusoidal.

Crest factors were around 1.41 corresponding to a perfect sinusoidal waveform. The twist lamp has a crest factor of 1.65 and the bayonet model 1.35. Signals were a little distorted, peaky and "flat-toped" (Fig. 8).

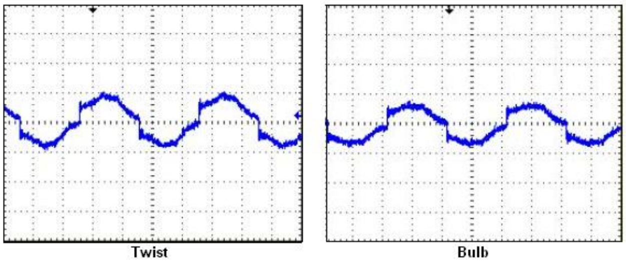

Fig 8: Lamp 8 and 9 current waveforms - 100mA, 5ms.

Total Harmonic Distortion and Power Factor were also very good and complied perfectly with all international requirements: 15.4% THD*i* and 0.91 PF for the Twist; 19.3% THD*i* and 0.91 PF for the Bayonet. The Displacement Power Factor was 0.99 for the Bayonet base lamp. For the same model, the K-Factor was 3.6 which is less than the value expected for a CFL. The K-Factor of the Twist is a little higher at 4.6, but still within limits. With regards to the bayonet version, it must be noted that the power consumed is much less than that given by the manufacturer: 10.7W instead of 13W and very low input current of 48mA instead of 60mA.

These two HP lamps comply perfectly with both requirements of the IEC 61000 standard.

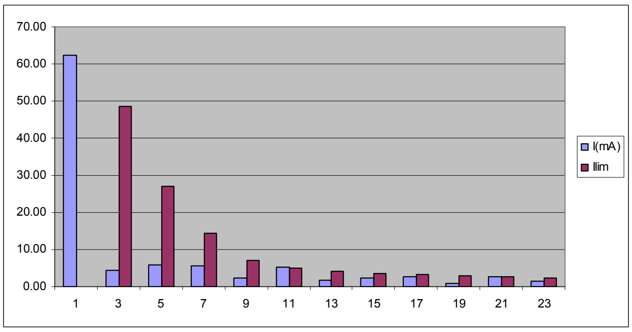

Fig 9: FFT and comparison with the standards for an HP lamp.

Regarding harmonics, the magnitude is much lower than the fundamental (Fig 9). The highest harmonic is the 5th and only represents 7% of the fundamental. The first odd harmonics; 3rd, 5th, 7th, were considerably below the limits.

It is clearly evident from this research that a high performance lamp is achievable within the price range of residential users. On the other hand, it is also important to note that many lamps that are sold in the market do not comply with even the less stringent parts of international standards. With the world moving towards a more non-linear load based power demand, the low power quality devices will place an extra burden on our transmission and distribution network.

V. Conclusions

The aim of the research was to neutrally analyse the power quality of CFLs available in the New Zealand market for residential use. The results obtained were compared with the international requirements.

Among the brands tested, there is only one brand that perfectly complied with the standards. The high performance lamps 8 and 9 presented high power factor (around 0.93) that is associated with THD*i* lower than 20%. Conversely, all the other models results were far from the first requirement of the standard and may not even pass the less stringent second, alternate, requirement. Power Factors for low performance bulbs were never greater than 0.6. While the current waveforms related to high performance products were almost sinusoidal, the current shape of the low performance bulbs was highly distorted.

Since this research was completed, and as a direct result of this research, a "New Zealand Only" clause has been added to AS/NZ 61000-3-2:2003 in order to improve the standard for New Zealand by effectively removing the second, weaker, requirement (second bullet point).

TABLEIII
AVERAGE VALUES OF THE LAMPS TESTED

	1	2	3	4	5	6	7	8	9
Irms(mA)	101	110	116	90.2	118	104	108	48	63.4
Power(W)	14.4	15.9	15.3	11.7	16.5	13.1	14	10.7	14.3
THDi(%)	133.1	116.86	123.1	120.7	127.3	132.8	113.5	15.4	19.3
PF	0.58	0.59	0.54	0.53	0.57	0.53	0.53	0.91	0.91
DPF	0.98	0.98	0.91	0.87	0.93	0.86	0.83	0.99	0.97
Crest-Factor	4.2	3.75	4.48	4.07	3.86	3.83	3.83	1.38	1.64
K-Factor	85.31	68.79	52.68	78.82	85.8	92.03	67.6	3.6	4.6
D-Power(Vad)	19.98	21.49	23.05	17.55	22.97	19.46	20.43	4.79	4.83
Harmoincs(mA):									
1	62.37	69.18	71.51	56.89	74.99	62.31	71.61	45.71	62.37
3	49.55	48.98	51.88	45.19	59.57	49.55	49.55	2.57	4.42
5	32.73	32.36	34.28	29.85	37.58	34.28	35.89	3.24	5.82
7	29.85	29.51	37.58	26	34.28	32.73	29.85	3.27	5.69
9	27.23	24.55	31.26	26	26	28.51	23.71	1.95	2.21
11	15.67	14.13	22.62	19.72	11.35	22.65	14.96	2.04	5.31

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