The Electrical Performance of Modern Compact Fluorescent Lamps

Sean Elphick (BE (Elec) (Hons)), University of Wollongong,
Philip Ciufo (BE (Hons), ME (Hons), PhD, SMIEEE), University of Wollongong,
Sarath Perera (BSc (Eng), MEngSc, PhD, MIEEE), University of Wollongong

Abstract

Compact Fluorescent Lamps (CFL) are highly non-linear devices which are likely to experience very high growth in penetration levels, especially in domestic environments, in Australia over the next 2 – 3 years. This will occur due to the decision taken by the Australian Federal Government to ban the sale of incandescent light globes after 2009 as measures towards meeting the needs for demand side management and climate change abatement. While CFL technology has been in existence since the late 1980s penetration levels are now increasing to a point where the total CFL load cannot be considered negligible compared to other non-linear domestic loads.

This paper seeks to redress the lack of concise data available describing the performance of modern CFLs over a range of influence factors such as input voltage magnitude and harmonic distortion. It seeks to provide definitive characterisation of the modern CFL in terms of harmonic and power factor performance over a range of input supply conditions. This aim is achieved through laboratory testing of 25 CFLs of different brands, construction types and rated power levels.

1. Introduction

The electrical performance characteristics of CFLs are strongly dependant on the design of the ballast used to drive the lamp. Development of the CFL over the last 20 years has seen magnetic ballasts replaced exclusively with electronic ballasts. Electronic ballast technology has developed to a point where there are now several ballast types available including some which aim to minimise the impact of the CFL on the quality of the ac supply feeding the CFL.

It is well known that CFLs are a non-linear load with significant current waveform distortion and poor power factor (without distinction being made between true and displacement power factor). With rising CFL penetration levels there are concerns that CFLs will lead to increased voltage harmonic distortion problems which will be difficult to mitigate given the distributed nature of domestic lighting loads.

There are several studies (Etezadi-Amoli & Florence, 1989; Finn & Ouellette 1992; Topalis, 1993; Pilleggi et al, 1993; Verderber et al 1993) from late 1980s and early 1990s which investigate the harmonic and power factor characteristics of the CFL. At that time, electronic ballasts for CFLs were an emerging technology and many of these studies report the outcomes of testing and analysis of both magnetically ballasted and electronically ballasted CFLs. As expected the majority of these studies report high current THD levels (greater than 100%). The studies which examine power factor find true power factors between approximately 0.4 and unity. However, power factor is not dealt with care in many of the studies with the distinction between true and displacement power factor regularly omitted. Without this distinction, the concept of leading or lagging power factor cannot be applied as it is not relevant to true power factor.

Although there is no reason to doubt the veracity of the studies reported in the aforementioned studies, they are now quite dated. At the time of these studies, CFLs, especially those with electronic ballasts were an emerging technology. It is evident that some developments to CFL ballast technology have occurred since their inception in the 1980s. An example of ongoing CFL technology development can be found in (Finn & Ouellette, 1992) and (Verderber et al, 1993) which refer to a new technology in ballasts which can limit harmonic distortion, although no reference is made to studies on these new devices.

In recent years, energy efficiency has become an issue that has received a considerable attention for various environmental, commercial and political reasons. Consequently, the introduction of CFLs is now seen as an important energy saving initiative.

Recent studies covered in (NEMA, 1999; Watson et al, 2007; Hansen, 2006; Watson, 2005; Gonos et al, 1999) present electrical characteristics of the CFL. Modern CFLs without power factor correction circuitry have been noted to produce current THD levels greater than 100%. Power factors ranging between 0.4 and 0.48 are reported in (Gonos et al, 1999). Studies of CFLs which include power factor correction circuitry indicate that this type of CFL is characterised by current THD levels significantly less than those of standard CFLs. The study presented in (NEMA, 1999) appears to be the first to report the performance of a power factor corrected CFL. It reports that standard CFLs have power factors of 0.5 compared to 0.8 or 0.9 for power factor corrected types. The study presented in (Watson, 2005) is a comparison of the performance of a high power factor type CFL with a standard un-corrected CFL. The high power factor CFL is found to perform significantly better than the standard CFL with respect to harmonics and power factor. For the high power factor CFL, current THD has been found to be approximately 17% compared to 124% for the un-corrected CFL.

While more recent studies covered in (NEMA, 1999), (Watson et al, 2007), (Hansen, 2006), (Watson, 2005) and (Gonos et al, 1999) have been conducted utilising modern instrumentation with modern CFLs, they are less than comprehensive in describing the methodology or reporting of findings or both. Studies (Hansen, 2006) and (Watson, 2005) use un-calibrated and unregulated sources to conduct the experiments. This is less than ideal as any distortion on the input voltage waveform can affect the results of the tests. None of the studies investigate the full harmonic spectrum of the input current waveform, instead only reporting on THD. It is important to identify the characteristic harmonics of the current waveform due to the fact that high order harmonics have behaviour, limits and potential effects which can be quite different to those of lower order harmonics. Reporting of power factor in these studies is also often ambiguous.

Notwithstanding the limitations of the above studies which report on the electrical characteristics of CFLs, very few studies examine the electrical characteristics of modern CFLs over a range of operating conditions and influence factors, such as variation in supply voltage levels and/or background voltage harmonic distortion, conditions which are likely to be present on electricity distribution networks in general, let alone the specific case of Australian electricity networks. The studies presented in (Ouellette & Arseneau, 1992) and (Cunill-Solà & Salichs, 2007) investigate the impact of voltage variations on CFL performance. Both find that input voltage magnitude will have an impact on CFL performance. However, the results found in each are contradictory. CFLs connected to the electricity distribution network are also likely to be exposed to some level of harmonic distortion on the input voltage waveform. The study presented in (Watson, 2005) indicates that this will affect the current harmonics drawn by the CFL. However, this study does not explore the effects of voltage input waveform distortion on the electrical characteristics of the CFL. Effects of supply voltage harmonics on CFLs are covered in (Arseneau & Ouellette, 1992) where both magnetic and electronic ballasts have been tested. It has been found that CFLs with magnetic ballasts are less affected by supply harmonics than those with electronic ballasts. Current THD has been found to deteriorate as the supply voltage harmonic distortion levels are increased.

This paper seeks to redress the lack of concise data describing the performance of modern CFLs over a range of influence factors. It seeks to provide a definitive characterisation of the modern CFL in terms of harmonic and power factor performance over a range of input supply conditions. To achieve this, 25 modern electronically ballasted CFLs of various ratings of various brands and designs have been laboratory tested using a programmable voltage source. Such testing allows understanding of the behaviour of the CFL under a range of conditions so that accurate modelling and simulations can be undertaken in order to assess the potential impacts of high CFL penetration levels on electricity networks. Some past studies have been carried out using simplified CFL models applied to distribution networks. However, if the performance of CFLs is heavily influenced by network operating voltages these studies can be considered as overly simplistic.

This paper is organised as follows: Section 2 describes the CFLs tested and the testing methodology adopted. Section 3 details the performance of the CFLs when subjected to a range of input voltage conditions. Conclusions are given in Section 4.

2. CFLs Tested and Testing Methodology

2.1 Test CFLs

As listed in Table 1, a total of 25 different modern CFLs have been tested. These CFLs represent a range of brands, construction types and ratings from a cross section of manufacturers, designs and price levels. All of the CFLs tested, with the exception of Lamp P, are standard non-power factor corrected types. Lamp P is a power factor corrected type CFL which contains additional components designed to mitigate input harmonic currents.

Table 1: List of CFLs Tested

Reference Label	Construction (Spiral/Straight)	Nominal Rating (W)
A	Spiral	15
B	Spiral	8
C	Straight	15
D	Straight	14
E	Straight	11
F	Straight	20
G	Straight	11
H	Spiral	15
I	Straight	15
J	Straight	15
K	Straight	11
L	Spiral	20
M	Straight	15
N	Straight	11
O	Straight	15
P	Spiral	15
Q	Straight	11
R	Spiral	15
S	Spherical	20
T	Straight	11
U	Spiral	11
V	Straight	14
W	Straight	18
X	Straight	18
Y	Straight	10

2.2 Test Methodology

At the commencement of testing, each CFL under test was brand new. Prior to application of test voltages, each CFL was operated using an input voltage of 230V for a minimum of 1 hour to ensure correct operation. For testing, the CFLs were mounted with their base down in a test board. All tests were performed in an air conditioned laboratory where the temperature was regulated.

The testing procedure for all tests was as follows:-

- At the commencement of each testing period, the CFLs were first stabilised at 230V for 10 minutes
- Once stabilised, each test level was applied for 5 minutes to allow the CFL to stabilise at the test level.
- Measurements were then taken using a Hioki 3196 power quality monitor over a 10 minute period. The measuring instrument was configured to log fundamental and harmonic voltages and currents to the 50^{th} order, as well as power parameters (real, active and non-active power and displacement power factor) at 1 minute intervals.

The test data was then averaged to provide indicative values.

Test voltages were applied using a California Instruments MX30-3PI programmable source. When programmed for undistorted output waveforms, this device has a very low output voltage distortion level (~0.24% THD).

3. CFL Performance over a Range of Influence Factors

The Australian voltage standard, AS60038:2000 (Standards Australia, 2000), specifies a nominal low voltage range of 230V +10%/-6%. A further 5% voltage drop is allowed for in installation wiring. Thus any equipment connected to Australian public low voltage supplies is expected to operate over a voltage range of 230V +10%/-11%. In addition, every distribution network will have some level of background voltage harmonic distortion present. In this section of the paper, the performance of the CFLs when subjected to varying input voltages is examined. To begin, analysis of the CFL performance with undistorted nominal voltage (230V) is examined. This is followed by characterisation of the CFL for undistorted voltages at the upper and lower ends of the voltage range. Finally, the impact of background voltage harmonics on CFL performance is assessed.

3.1 Basic Characteristics

3.1.1 Current Waveforms

The majority of CFLs tested were characterised by highly distorted input current waveforms. Figure 1 shows a sample of 3 current waveforms observed, with the sinusoidal input voltage waveform shown for comparison. It can be seen that there is considerable variation in the shape of the current waveform drawn by the 3 different CFLs with these waveforms demonstrating the least distorted waveform, most distorted waveform and a waveform in between. The current waveform of Lamp P which has been designed to correct the power factor by minimising waveform distortion is particularly distinct.

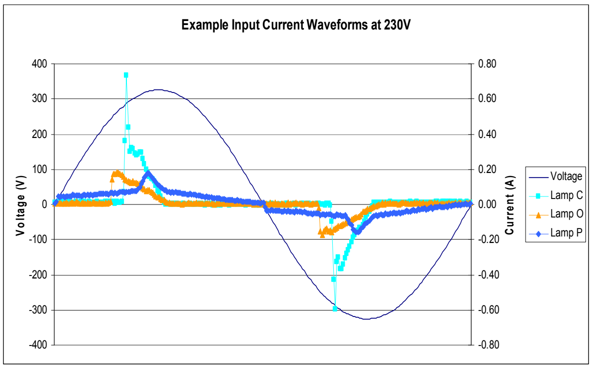

Figure 1: Selected CFL Input Current Waveforms

3.1.2 Harmonic Performance

The shapes of the current waveforms in Figure 1 suggest that the input current of the CFLs are rich in harmonics. Figure 2 shows the measured Current Total Harmonic Distortion (ITHD) for each CFL. It can be seen that all CFLs except Lamp P have ITHD levels close to or exceeding 100%. The maximum current ITHD level is 171% (Lamp Y). It can be noted that lamps with similar construction and rating display different ITHD behaviour. This indicates that while many CFL circuits are similar different manufacturers must produce lamps with different components values and circuit construction. Figure 3 shows the harmonic spectra of the CFLs displayed in Figure 1. Again, it can be seen that Lamp P has considerably better harmonic performance compared to other two CFLs. Of particular interest is the fact that the CFLs show harmonic currents of significant magnitudes up to very high harmonic orders which is not characteristic of most domestic appliances.

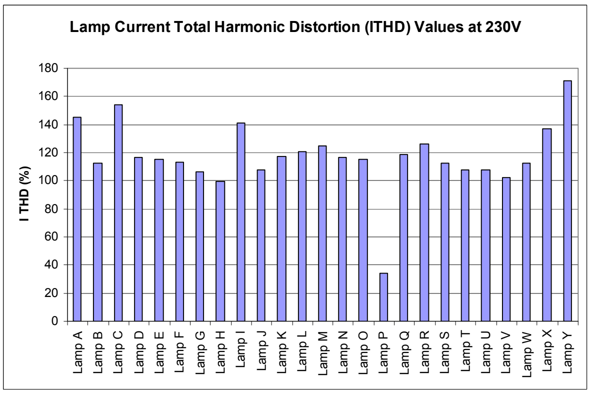

Figure 2: Current THD Levels for each Lamp

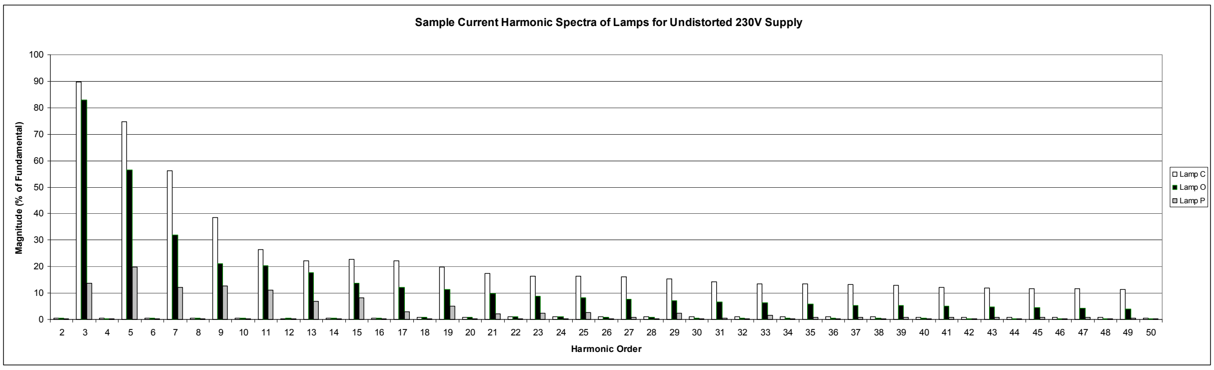

Figure 3: Sample Current Harmonic Spectra for Lamps Supplied by Undistorted 230V RMS

3.1.3 Power Factor Performance

Based on the displacement and true power factor values illustrated in Figures 4 and 5 the following observations can be made:

1. The displacement power factor of the CFLs is relatively high, averaging 0.89. The maximum is 0.98 for Lamp P, while the minimum is 0.81 for Lamp D. Displacement power factor is found to be leading in all cases. This suggests that the CFLs may provide some power factor correction to the traditionally inductive residential load. This is in agreement with results presented in (Watson et al, 2007).

2. The true power factor (ratio of active power to apparent power), for all CFLs with the exception of Lamp P can be found to be poor, averaging, 0.58. The high true power factor of Lamp P, at 0.92, indicates the effectiveness of the power factor correction technology included in this CFL.

3. The relatively high displacement power factor and poor true power factor associated with CFLs is due to harmonics and other non-fundamental components of the input current. This leads to apparent power levels that are considerably greater than active power levels.

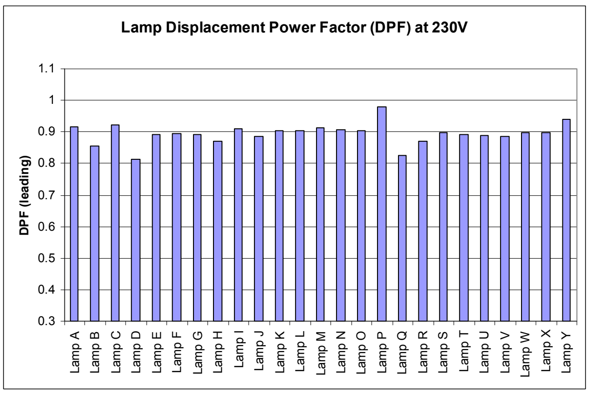

Figure 4: CFL Displacement Power Factor

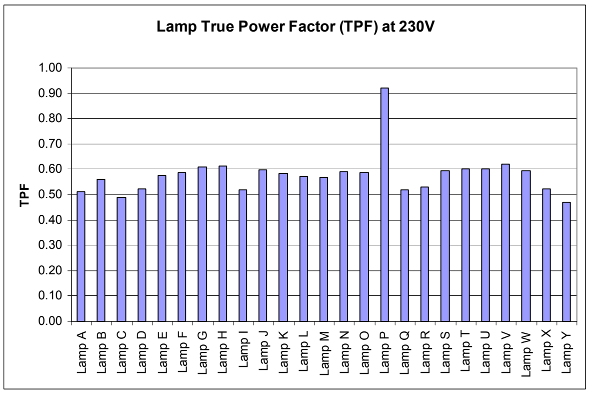

Figure 5: CFL True Power Factor

3.2 Effect of Varying Input Voltage Magnitude

In this section, the impact of variation of undistorted input voltage magnitudes on the performance of the CFLs is examined. To achieve this, three input voltage levels based on Australian Standard Voltages (Standards Australia, 2000) were applied to the CFLs. These were 253V RMS, which is the maximum allowable, 230V RMS which is the nominal and 207V RMS which is the lower end of the allowable voltage.

Figure 6 shows the variation of the RMS input currents for the CFLs when the input voltage magnitude was varied. The variation for each parameter for each CFL is calculated as a percentage difference between minimum and maximum values. This is achieved by subtracting the minimum value obtained for each test from the maximum value and then dividing by the minimum value to result in a percentage value. It can be seen that the RMS input current levels are relatively insensitive to changes in input voltage level with the average variation being approximately 5% and the maximum is approximately 10%. In all cases except for Lamp P RMS current levels increased as voltage magnitude was increased.

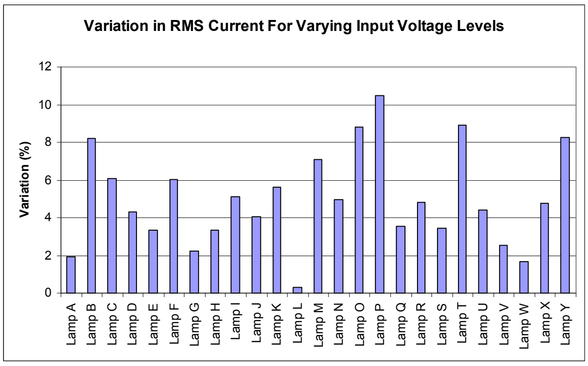

Figure 6: Variation in the RMS Current Levels for Different Lamps for Varying Input Voltage Magnitudes

A similar calculation can be carried out to assess the impact of variable input voltage magnitude on the fundamental current levels. It was found that the fundamental current drawn by the CFLs is even less sensitive to input voltage magnitude than the RMS current, with average variation across CFLs being 2% and maximum variation being 6%. In terms of the effect of input voltage variation on total current harmonic levels (total harmonic current is preferred to current THD as it is not reliant on the value of the fundamental current) the small variation in RMS current tends to suggest a small variation in harmonic currents as well. This is found to be the case for all CFLs with the exception of Lamp P which is the high power factor CFL. If Lamp P is excluded, the average variation in the total harmonic current is 8% and the maximum is 12% which is of the same order as the RMS current variation. In all cases (except lamp P), total harmonic current increased with voltage magnitude. Interestingly, Lamp P shows a 170% variation in current THD levels when the input voltage is varied, with total harmonic current levels decreasing with increasing supply voltage magnitude. This suggests a characteristic operation which is significantly different to that of the other CFLs with harmonic currents being highly dependant on input voltage levels.

For displacement power factor (DPF), the variation was found to be small, with the average being approximately 1.5% and the maximum being approximately 3%.

The information given above is summarised in Table 2 which shows the variation of key parameters as input voltage magnitude is varied.

Table 2: Variation of Key Parameters with Varying Input Voltage Magnitudes

Parameter	Average Variation (%)	Maximum Variation (%)
RMS Current	5	10.5
Fundamental Current	2.6	6.1
Total Harmonic Current	8.1	170.3
Displacement Power Factor	1.5	2.6

3.3 Effect of Varying Input Voltage Distortion Levels

In order to gain an understanding of the impact of distorted input voltages, a number of tests were carried out on the CFLs using input voltages with varying harmonic distortion levels.

Data collected by the Australian Long Term Power Quality Survey (Power Quality Australia, 2008) as well as other field monitoring campaigns indicate that voltage THD levels will be less than 3.67% at 95% of Australian sites with the dominant harmonic order being the 5th. Other orders which make meaningful contributions are low order odd harmonics such as 3rd and 7th. Higher order harmonics have been noted to be generally small. Further, most supply voltage waveforms exhibit a flat top characteristic. This allows basic determination of the phase angle of the harmonic voltages. Such flattening can be shown to be caused by a 3rd harmonic component which has a phase angle of close to 0 degrees with respect to the fundamental and a 5th harmonic component which has a phase angle close to 180 degrees with respect to the fundamental. Field monitoring confirms these observations. Field monitoring also demonstrates a 7th harmonic phase angle close to 50 degrees. Given this data, the following two test waveforms were developed (note all values in % of 230V):

- Test Waveform 1 – 1% 3rd harmonic with a phase angle equal to 0, 3% 5th harmonic with a phase angle equal to 180 degrees, 1% 7th harmonic with a phase angle equal to 50 degrees.
- Test Waveform 2 – 2% 3rd harmonic with a phase angle equal to 0, 4% 5th harmonic with a phase angle equal to 180 degrees, 1.5% 7th harmonic with a phase angle equal to 50 degrees.

The above waveforms have THD levels of 3.3% and 4.7% respectively.

Table 3 shows the variation of key parameters for the case of the undistorted waveform and the case of Test Waveform 1. It can be seen that the variation of key parameter values between the undistorted case and the distorted case is quite small. For tests using Test Waveform 1, on the 25 CFLs, 17 CFLs recorded an increase in RMS current with increased input voltage distortion and 18 showed increases in total harmonic current with increased input voltage harmonic distortion. All of the CFLs recorded a decrease (worsening) of leading displacement power factor although the change could be considered insignificant.

Table 3: Variation of Key Parameters for Distorted Input Voltages – Test Waveform 1

Parameter	Average Variation (%)	Maximum Variation (%)
RMS Current	1.7	6.9
Fundamental Current	-0.7	5.1
Total Harmonic Current	2	7.1
Displacement Power Factor	-1.6	-2.9

Table 4 shows the variation of the key parameters between the undistorted case and Test Waveform 2. It can be seen that the values obtained are larger than those for test waveform 1 but still considerably smaller than those obtained using the basic tests. For tests using test waveform 2, 23 CFLs recorded an increased RMS current with increased input voltage distortion and all recorded increased total harmonic current with increased input voltage distortion.

Table 4: Variation of Key Parameters for Distorted Input Voltages – Test Waveform 2

Parameter	Average Variation (%)	Maximum Variation (%)
RMS Current	4.6	9.1
Fundamental Current	-2	3.3
Total Harmonic Current	7.9	23.7
Displacement Power Factor	-1.2	-2.2

Comparing the values in Table 3 with the values obtained for the tests involving varying input voltage magnitude in Table 2, it can be seen that similar variations are observed in key parameters when either input voltage magnitude or input voltage distortion are varied with variation in voltage magnitude being slightly more important than variation in input voltage distortion levels.

4. Conclusions

This paper has provided a definitive characterisation of the electrical behaviour of the modern CFL. While a number of studies have been undertaken in this area many are now quite dated. The more recent studies give ambiguous results with regards to data reporting techniques or testing methods.

The basic operation of the standard CFL, based on testing of 25 modern CFLs from a variety of manufacturers, when subjected to an undistorted 230V RMS voltage is as follows:

1. Current THD levels are generally >100%. The maximum is 171%
2. Displacement power factor is high, with the average being 0.89 and is leading for all CFLs tested.
3. True power factor is poor due to high current harmonic content, with the average being 0.58 and the minimum being 0.47.

The high power factor CFL behaved quite differently to the standard CFL and was characterised by a current THD level of 34%, a displacement power factor of 0.97 and a true power factor of 0.96, when an undistorted 230V supply was used. This represents a significantly better performance compared to the other CFLs tested.

The effect of various influence factors on CFL performance has also been examined. Tests were carried out to assess the impact of variation in input voltage magnitude as well as variable input voltage harmonic distortion levels.

Overall it was found that variations in input voltage magnitude and distortion levels for values likely to be encountered on electricity distribution networks has little effect on the performance of the standard CFL. However, interestingly, the total harmonic current of the high power factor CFL was found to be highly sensitive to input voltage magnitude. All CFLs were found to be slightly more sensitive to input voltage magnitude than input voltage distortion level for realistic values of each. Little change was observed in fundamental current and displacement power factor levels, however, RMS current and total harmonic current was affected to some extent when input voltage magnitudes and distortion levels were increased.

These results are significant because they provide an indication of the performance of CFLs under a range of influence factors. This is necessary if accurate models of CFLs are to be developed for use in simulations designed to assess the impact of CFLs on the electricity distribution network.

5. Acknowledgements

The authors would like to acknowledge the contribution of the Australian Strategic Technology Programme (ASTP) of the Energy Networks Association who provided funding for much of the work presented in this paper.

6. References

R. Arseneau, M. Ouellette, "The Effects of Supply Harmonics on the Performance of Compact Fluorescent Lamps", IEEE Transactions on Power Delivery, Vol. 8, No. 2, April 1993

M. Etezadi-Amoli, T. Florence, "Power Factor and Harmonic Distortion Characteristics of Energy Efficient Lamps", IEEE/PES 1989 Winter Meeting, New York, New York, Jan 29 - Feb 3, 1989

Jordi Cunill-Solà, Miquel Salichs, "Study and Characterization of Waveforms from Low-Watt (<25W) Compact Fluorescent Lamps with Electronic

Ballasts”, IEEE Transactions on Power Delivery, Vol 22, No. 4, October, 2007

D. W. Finn, M. J. Ouellette, "Compact Fluorescent Lamps: What You Should Know", National Research Council Canada; Originally Published in Progressive Architecture, Aug 1992, http://www.irc.nrc-cnrc.gc.ca/pubs/cp/lig3_e.html, last accessed, 1/3/2007

I. F. Gonos, M. B. Kostic, F. V. Topalis, "Harmonic Distortion in Electric Power Systems Introduced by Compact Fluorescent Lamps", PowerTech Budapest 1999, International Conference on Electrical Power Engineering, 29 Aug - 2 Sep, Budapest, Hungary, Page(s):295

Tony Hansen, "Compact Fluorescent Lamp (CFL) Comparison Testing", Report to Integral Energy, December 2006

NEMA Lighting Systems Division, "Power Quality Implications of Compact Fluorescent Lamps", Report prepared by National Electrical Manufacturers Association (NEMA) (USA) Lighting Systems Division, April 1999

Michael J. Ouellette, Réjean Arseneau, "The Effects of Undervoltage on the Performance of Compact Fluorescent Systems", IEEE Industry Applications Society Annual Meeting, 4 - 9 Oct 1992, Page(s):1872 - 1879 vol.2

D. J. Pileggi, E. M. Gulachenski, C. E. Root, T. J. Gentile, A. E. Emanuel, "The Effect of Modern Compact Fluorescent Lamps on Voltage Distortion", IEEE Transactions on Power Delivery, Vol. 8, No. 3, July, 1993

Power Quality Australia, 2006–2007 Long Term National Power Quality Reports, Confidential reports to participants, 2008

F. V. Topalis, "Efficiency of Energy Saving Lamps and Harmonic Distortion in Distribution Systems", IEEE Transactions on Power Delivery, Vol. 8, No. 4, October 1993

Rudolph R. Verderber, Oliver C. Morse, William R. Alling, "Harmonics from Compact Fluorescent Lamps", IEEE Transactions on Industry Applications, Vol. 29, No. 3, May/June 1993

Standards Australia, AS60038-2000, "Standard Voltages", 2000

Neville R. Watson, Tas Scott and Stephen Hirsch, "Compact Fluorescent Lamps (CFL) - Implications for Distribution Networks", 83rd Annual EESA Conference and Exhibition, Electricity 2007, Melbourne, Australia, 15 - 17 Aug 2007

N. R. Watson, "A Comparison of the Philips Tornado Compact Fluorescent Lamp with the new High Power-Factor Eco-Bulb”, http://www.ecobulb.com/files/Report_Harmonics_Feb2005.pdf, last accessed 30/1/08