Parsons Brinckerhoff Associates

INSTALLATION OF COMPACT FLUORESCENT LAMPS
ASSESSMENT OF BENEFITS

A report prepared for

Electricity Commission
Te Komihana Hiko

April 2006

Disclaimer Notice

Report for the Benefit of the Electricity Commission

This Report has been prepared exclusively for the benefit of the Electricity Commission. Parsons Brinckerhoff Associates Ltd (PB Associates) will not be liable to any other persons or organisation and assumes no responsibility to any other person or organisation for or in relation to any matter dealt with or conclusions expressed in the Report, or for any loss or damage suffered by any other persons or organisations arising from matters dealt with or conclusions expressed in the report (including without limitation matters arising from any negligent act or omission of PB Associates or for any loss or damage suffered by any other party relying upon the matters dealt with or conclusions expressed in the Report). No person or organisation other than the Electricity Commission is entitled to rely upon the Report or the accuracy or completeness of any conclusion and such other parties should make their own enquiries and obtain independent advice in relation to such matters.

Reliance on Data

In preparing this Report, PB Associates has relied on information supplied by and gathered from a number of sources including public domain and proprietary data services, internet sites, news services as well as parties involved in the industry. No blame or responsibility should be attached to any of these sources for any factual errors or misinterpretation of data in this Report. PB Associates has not independently verified the accuracy of this information.

Limitations

This Report is based on technical, electrical and financial data relating to compact fluorescent lamps and is based on the facts known to PB Associates at the time of preparation. This Report does not purport to contain all relevant information. PB Associates has made a number of assumptive statements throughout the Report and the Report is accordingly subject to and qualified by those assumptions. The uncertainties necessarily inherent in relying on assumptions and projections in the energy market mean that it should be anticipated that certain circumstances and events may differ from those assumed and described herein and that such will affect the results.

Parsons Brinckerhoff Associates Ltd

Level 3, Hitachi House
48-54 Mulgrave Street
Wellington
Phone ; +64 4 499 1000
Fax : +64 4 916 6514

TABLE OF CONTENTS

Sections

EXECUTIVE SUMMARY 1

1. INTRODUCTION 3
   - 1.1 General 3
   - 1.2 Methodology 3
     - 1.2.1 Evaluation of power quality implications 3
     - 1.2.2 Assessment of economics of installation 3
   - 1.3 Sources of Information 4
2. ASSESSMENT OF POWER QUALITY IMPLICATIONS 5
   - 2.1 Introduction 5
   - 2.2 Background 5
   - 2.3 Reliability 6
   - 2.4 Power Factor 8
   - 2.5 Harmonics 9
   - 2.6 Improving Power Quality 11
   - 2.7 Maximum Penetration 12
   - 2.8 International Standards 13
   - 2.9 Experience Elsewhere 15
3. ECONOMICS OF INSTALLATION 16
   - 3.1 Introduction 16
   - 3.2 Key Assumptions and Scenarios 16
   - 3.3 Cost of Installation 16
   - 3.4 Electrical Energy Saved By Customer 17
   - 3.5 INCREMENTAL Network Capacity Savings 18
   - 3.6 Electricity Saved/Avoided - Marginal Cost of Generation 19
   - 3.7 Generation Investment Avoided 20
   - 3.8 Impact on Electrical Peak Load 20
   - 3.9 CO_2 Abated – Volume and Value 22
   - 3.10 Impact on Infrastructure 23
   - 3.11 Cost of Power Factor Correction Equipment and Harmonic Filtering 26
4. CONCLUSIONS 28
5. RECOMMENDATIONS 31

Appendix A - References

Appendix B – Summary of Costs/Benefits

GLOSSARY OF TERMS

Term	Definition
AC	alternating current
ANSI	American National Standards Institute
CFL	compact fluorescent lamp
CO_2	carbon dioxide
ELC	European Lighting Companies Federation
GWh	giga watt hours (10^9 watt hours)
HPF	high power factor
I	current
IEC	International Electrotechnical Commission
kVA	Kilovoltamp - reactive
kVar	kilovar
kW	kilowatt
kWh	kilowatt hour
LPF	low power factor
mA	milliamp
MW	Megawatt
mW	milliwatt
MWh	Megawatt hour
n	harmonic order
NZECP	New Zealand Electrical Code of Practice
pf	power factor
QC	quality charter
R	resistance
THD	total harmonic distortion
V	volt
VA	volt amp
VFD	variable frequency drives
W	watt

EXECUTIVE SUMMARY

Introduction

Parsons Brinckerhoff Associates was asked by the Electricity Commission to evaluate the principle power quality implications associated with the introduction of Compact Fluorescent Lamps (CFLs) in residences, specifically regarding power factor and harmonics.

A comparison was drawn between low power factor and high power factor CFLs to determine if there are any measurable advantages of using high power factor bulbs in terms of an improvement in system power quality.

In drawing conclusions, consideration was given to industry best practice standards and relevant past international experience.

The economics of installing CFLs with a high power factor were examined, including a cost/benefit analysis. Throughout the analysis, a case study was considered, which assumed 5 CFLs were installed per household in 400,000 homes in the Auckland area. This case study served to quantify benefits associated with CFLs in terms of electrical energy saved, CO_2 emissions avoided, impact on peak load and generation and distribution investment.

Evaluation Framework

The cost/benefit evaluation framework addressed the cost and benefits of installation of CFLs. Four key areas formed the evaluation framework:

- electrical energy (kWh) saved and associated value;
- CO_2 abated and associated value;
- impact on peak demand and potential to avoid investment in distribution and transmission networks; and
- variation in the incremental cost of upgrading from Low Power Factor (LPF) CFLs to High Power Factor (HPF) CFLs versus the cost of capacitive compensation and harmonic filtering equipment.

Conclusions

- There has been some reluctance by users in the past to use high power factor CFLs as poor quality products were released onto the marketplace, with correspondingly low life-spans. However, recent tests performed in New Zealand indicate that the technology is now available to produce superior quality high power factor CFLs and the market penetration is rapidly increasing.

- With increased market penetration, power quality issues are expected to arise, in particular increased harmonic voltage levels and reduced power factors.

- It is possible that higher harmonic content will have an impact on old technology ripple control systems.

- The current New Zealand standard on harmonics, AS/NZS 61000.3.2:2003, is less stringent than its European counterpart when it comes to the highest harmonic limits allowable. It is predicted that tougher power factor and harmonic standards will be proposed for CFLs with the review of the international voluntary standards.

- High and low power factor CFLs deliver the same electricity savings to the householder, so there is no incentive on the end user to pay more for a higher power factor CFL.
- Network capacity savings are significantly higher for high power factor CFLs.
- Both types of CFL provide a useful reduction in peak demand.
- Both types of CFL provide a useful reduction in generation requirements and the potential to avoid new generation investment.
- Both types of CFL provide a useful reduction in CO_2 emissions.
- The initial incremental cost of installing HPF-CFLs instead of LPF-CFLs is approximately 10 times less than the cost of capacitive compensation equipment which might become necessary to counteract the degradation in power factor caused by using LPF-CFLs.

Recommendations

- To adopt a preventative approach towards possible power quality problems by:
    - Performing more localised CFL penetration studies on the New Zealand power system, especially in areas of the network susceptible to poor power quality problems and ensuring that the connected equipment will continue to operate as intended in the presence of the pre-determined harmonic distortion.
    - Reviewing and tightening existing standards and guidelines. Given the number of unknowns about the impacts of large numbers of CFLs on power quality and due to the increasing number of non-linear loads on the system, it is recommended that high importance is given to controlling power factor and harmonic distortion, though the review and tightening of existing CFL specifications
    - Agreeing on suitable test protocols to be followed by all manufacturers with respect to power quality. This will eliminate the risk of poor power quality CFLs entering the marketplace, reduce the risk of a monopoly supplier and serve to increase customer satisfaction and CFL usage.
    - Taking the lead on promoting good quality products, assuming the perceived benefits outweigh the costs. Keep in mind that good quality electronic ballasts should be capable of reaching power factors of 0.95 or greater. To consider introducing product guarantees to gain consumer trust and improve consumer satisfaction.
    - Paying close attention to the results of current working groups charged with reviewing international harmonics standards.
- To adopt a risk management approach in assessing each available option and to perform an assessment of the preventative measures and remedial actions available with each option. I.e. Is it more difficult to prevent and tackle the problem of premature ageing associated with HPF-CFLs or to prevent and tackle the power quality problems associated with LPF-CFLs.
- To consider incentives to overcome the initial high cost of high quality CFLs.

1. INTRODUCTION

1.1 GENERAL

Parsons Brinckerhoff Associates was asked by the Electricity Commission to:

- evaluate the main power quality implications associated with the introduction of Compact Fluorescent Lamps (CFLs) in residences; and
- examine the economics of installing CFLs with a high power factor, including examining the incremental cost of upgrading from standard power factor bulbs to higher power factor bulbs and the associated cost/benefits.

This study focuses on the installation of 5 CFLs in each of 400,000 homes in the Auckland region.

1.2 METHODOLOGY

1.2.1 Evaluation of power quality implications

The investigation into power quality was undertaken by:

- performing a search for case studies detailing past national and international experience relating to CFLs and power quality;
- comparing current power quality standards and protocols to determine differences between countries; and
- speaking to network operators, manufacturers, researchers, standards review panel members.

This analysis is contained in Section 2.

1.2.2 Assessment of economics of installation

The assessment of the economics of installation, including a cost/benefit analysis covered the following issues:

- electrical energy avoided/saved;
- marginal cost of electrical energy avoided/saved;
- generation investment avoided;
- impact on peak demand (kW) and potential to avoid transmission investment;
- CO_2 Abated – volumes and values;
- impact on infrastructure; and
- initial incremental cost of HPF-CFLs vs. the cost of power factor correction and harmonic filtering equipment that may be necessary as a result of using LPF-CFLs.

The evaluation of electricity issues has been made in the context of electrical demand in the Auckland area and the supply-side constraints that currently characterise that market.

Potential CO_2 savings have been evaluated in the context of New Zealand's projected net national position under the Kyoto first commitment period (2008 to 2012), and recent international developments in CO_2 emissions trading. From a national perspective, it is important both to evaluate volumes of potential CO_2 savings and their associated likely cost, and compare these with alternative abatement methods. This analysis is contained in Section 3.

1.3 SOURCES OF INFORMATION

In preparing this report, we have relied upon information supplied to us and gathered from a number of sources, including public domain information and the internet. We have not sought to verify this information nor have we undertaken any original research.

In particular, we highlight our use of:

- available public domain power quality publications and demand forecasts for electricity in the Auckland area;
- existing studies into CFLs in New Zealand, particularly regarding technical output and cost related information, provided to us by the Electricity Commission; and
- information from various sources working in this area.

Our use of sources is referenced throughout the report and a list of references is provided in Appendix A.

2. ASSESSMENT OF POWER QUALITY IMPLICATIONS

2.1 INTRODUCTION

In recent years, concerns about the effects of fluorescent lighting products on power distribution systems have focussed attention on power quality issues. Historically, electricity distribution systems were not adequately designed to deal with a great quantity of non-linear loads. Up until now power quality issues associated with CFLs have largely been ignored as the number of these lamps on the system was small and the associated impact difficult to quantify. However, the situation is likely to change in the near future as large numbers of CFLs penetrate the marketplace and, as a result, harmonic emissions may have to be limited.

The purpose of this paper is to examine the main power quality implications associated with the introduction of CFLs in residences and from this, to ascertain if there are advantages in using high power factor CFLs as an alternative to low power factor CFLs.

Power quality has been defined by the IEE to consist of two aspects: reliability of supply and voltage quality. Reliability of supply is determined by the number and duration of power interruptions. Voltage quality is affected by distortions of the waveform, which are deviations from the ideal sinusoidal voltage curve caused by voltage fluctuations, voltage dips, harmonics, flicker and transients. Harmonics are a major concern associated with non-linear loads and as such harmonics and their relationship with power factor shall be discussed in this paper.

A case study is included that consists of 400,000 homes in the Auckland area with an assumption that there are 5 CFLs per household. An assessment of how this might affect the Auckland power system in terms of power quality is undertaken along with a cost/benefit analysis of installing the CFLs. This cost/benefit analysis covers such items as electricity saved, CO_2 emissions avoided, impact on winter peak demand and investment in generation and the distribution systems.

In drawing the conclusions of this study, consideration is given to industry best practice standards and relevant international past experience, from a power quality perspective.

2.2 BACKGROUND

A primary reason for using CFLs is the savings that can be achieved in terms of energy and running costs, which benefit the householder. Due to their higher efficacy, a 25 watt (W) CFL can provide the equivalent light output to a 100 W incandescent bulb. This represents a reduction in wattage of close to 75%. A CFL also lasts around ten times as long as an incandescent lamp.[1] The high initial cost of a CFL can therefore be paid quickly through the resultant energy savings and avoided cost of replacement incandescent bulbs. The actual length

[1] Manufacturer’s information

of the pay back period is dependent on the annual operating hours as well as the relative bulb prices and the cost of electricity.

Up until now there has been much negativity expressed by consumers towards the CFL technology. A major problem has been a lack of knowledge about the characteristics of CFLs, exacerbated by the wide range of CFLs available. Consumer resistance may be largely due to bad experiences with the early technology or low-quality products.

CFLs have the disadvantage of operating at lower power factors than incandescent lamps and this has implications for the design and operation of the power system. Non-linear loads reduce power factor because of the higher RMS currents caused by the pulsed nature of the input current.

CFLs, like all discharge lamps, create harmonics on the supply system because of the control systems limiting the plasma (an electric arc) current, which produces the light. Newer types of CFLs have electronic ballasts operating at high frequency. The magnitudes of the harmonics generated by the CFLs vary between manufacturers and between the ranges of lamps. It has been proven that HPF-CFLs tend to reduce the level of harmonic distortion.

Harmonics can cause a variety of network problems – transformer and cable overheating (hence lowering lifespan), motor overheating, premature ageing of capacitors, interference with telecoms systems, possible disturbance in ripple control systems (hot water).

This report is intended to look at the downside impacts in more detail in order to provide a balanced assessment of the impact of a greater penetration of CFLs and to determine how the downside problems can be mitigated.

2.3 RELIABILITY

In the early stages of CFL electronic ballast development high failure rates were recorded for HPF ballasts. This led to a perception amongst those in the industry and amongst potential users that the technology was unreliable. One reason for this was that, in the early days of manufacture, lamps were not necessarily tested and sold in the country of manufacture and designs did not allow for voltage variations on international power systems. Therefore, the lifespan of these lamps often proved disappointingly short.

The Irish utility, ESB, used Chinese made CFLs in their first CFL initiative as they had the best power quality characteristics available at the time. However, there was an early bulb failure rate of approximately 25% and the program was temporarily abandoned.[2] Lamp quality-both in terms of efficacy and life span is poorer in China than in many other parts of the world, especially western countries. Only less than 30% of the lamps produced meet international quality standards. Standard linear fluorescent lamp lifetimes in China range from 3,000 to 5,000 hours, compared with 10,000 to 20,000 for western manufacturers. However, recently countries like China and Brazil are placing more importance on controlling the power factor and harmonic distortion, as there is increasing potential for extensive CFL usage.

[2] China – A Lighting Giant, IAEEL 3/94
Confirmation from ESB Customer Supply

Documenting the reliability of manufacturers' products has proven to be a difficult process as designs and manufacturing processes are often changing. With the introduction of more CFL manufacturers into the market, increasing emphasis is being placed on product quality. With more and more lamps on sale, consumers will find it increasingly difficult to tell low-quality from high-quality lamps, and the reputation of CFLs could suffer as a result if adequate quality standards are not implemented.

Lamp life is related to many factors, one being the exposure to heating effects brought about by transient voltage fluctuations. Filters and voltage limiters in the lamp ballast are now used as a means to reduce or even eliminate unwanted heating effects. There are concerns that the HPF bulb has a higher probability of failure than the LPF bulb due to the increased number of electronic components exposed to heating effects. In response some manufacturers have implied that it is the quality and not the quantity of the electronic components that will determine lifetime, light output, etc. Recently, tests have been performed in New Zealand to examine the characteristics of various LPF and HPF bulbs when a sinusoidal voltage is applied. The results of these tests indicate that the technology is indeed available to produce good quality HPF lamps with superior power quality characteristics[3].

An EU project has recently commenced in Toulouse, encompassing two main aims[4]:

- to promote good quality CFLs for residential lighting; and
- to define what a good quality CFL is by updating the European CFL Quality Charter (CFL-QC).

The current CFL-QC contains a set of voluntary performance criteria for electronic CFLs. These criteria were established in collaboration with a number of private and public organisations, including energy agencies and the European Lighting Companies Federation (ELC).

In conjunction with this project, a working group has been formed to develop an approved European lamp ON-OFF cycle test procedure. Rapid ON-OFF switching of the CFL directly affects lamp quality and lifespan, the extent of which is large but not yet clearly proven. This is a very controversial topic in Europe at present and there has not been much agreement in the past regarding a suitable and fair European test procedure. Up to now, theoretical investigations have been undertaken into the ageing effects of CFLs but no solid experimental proof has been available. However a lamp ageing test setup has recently been put in place. It is hoped that the results of these experiments will provide the necessary information to develop an acceptable European testing procedure that all manufacturers will be required to adhere to.

At present, international standards lifetime testing only requires one switching cycle for three hours of lifetime (3,333 cycles for a 10,000hr bulb). The American Energy Star switching test requires one cycle per two hours (5,000 cycles for a 10,000hr bulb). It is expected that the CFL-QC will require the lamp to have at least as many ON-OFF cycles as the number of lifespan hours. Consideration may also be given to including voluntary power factor requirements within the

[3] Performance of Compact Fluorescent Lamps with Under-voltage – N.R. Watson
A Comparison of the Philips Tornado CFL with the new High Power Factor Ecobulb – N.R. Watson
[4] Information supplied from EU CFL-QC Project Review Team

CFL-QC. Recent tests have proved that the technology is readily available to produce HPF-CFLs with a switching lifetime equivalent to a NPF-CFL.

2.4 POWER FACTOR

Traditional displacement power factor can be defined as the ratio of real power to apparent power (Watts/VA). When dealing with linear loads, the displacement power factor is dependant upon the phase relationship between the current and voltage sine waves. When these waves are in phase, the power factor is unity. As the current and voltage waves move out of phase the displacement power factor reduces and the value of the power factor is a measure of the relative displacement of the two waves. The phase difference between the voltage and current waves can be reduced (and the displacement power factor increased) by adding inductance or capacitance to the system.

A distribution system is used most efficiently when the voltage and current waves are in phase since in this state the current required to produce a given quantity of real power is minimized. As the power factor reduces, utilisation of the distribution system is less efficient and distribution system losses increase as a result.

As incandescent lamps are almost purely resistive, the displacement power factor due to lighting will be close to unity. However, the introduction of CFLs will introduce a lagging power factor and out-of-phase current. In some international urban power systems it can be beneficial to introduce inductive loads to counteract the leading power factor present due to the capacitive effects of underground cabling. Due to these differences between power systems, the International Harmonizing Specifications[5] will feature varying power factors of between 0.5 and 0.9.

However, it is more common that a distribution system will have a lagging power factor, as is the case in New Zealand. In relation to the New Zealand power system, it is beneficial to have leading power factor loads to support a suitable harmonic characteristic and to obtain system savings.[6]

Most distribution networks now support a large number of electronic (non-linear) loads. Non-linear loads draw harmonic currents, which increases the apparent power that must be delivered, hence lowering the power factor. The power factor term that describes a system with both linear and non-linear loads is called true power factor [*Watts* / ($|Vrms|$ * $|Irms|$)]. Low values of true power factor are due to non-linear loads producing harmonic currents, converting useful power into useless - harmonic reactive power.

The true power factor of the system will always be lower than the displacement power factor. For example, the displacement power factor for a personal computer is 0.9 or greater but its true power factor can be as low as 0.6. Resistive loads, such as incandescent lamps, have a displacement power factor of unity. Electronic ballasts for fluorescent lamps, due to their inherent non-linear nature, may be either high power factor (HPF) or low power factor (LPF). A CFL

[5] Launched at the Right Light 6 Conference. The participants agreed to work together to create uniform international testing methods for CFLs and to identify a number of performance specifications for self-ballasted CFLs

[6] Electricity Commission – Discussion Paper – Funding Program for CFLs – December 2003

is defined to have a HPF if the displacement power factor is 0.9 or greater. A displacement power factor of between 0.5 and 0.9 is defined as LPF. Normally, good quality electronic ballasts should be able to achieve displacement power factors of 0.95 or greater.

While the true power factor calculation is applicable to power systems containing non-linear loads, the relevant power factor calculation method for the impact of CFLs and other harmonic sources on the transmission network (especially in voltage constrained areas such as Auckland) is the displacement power factor.

In typical household situations up until now, CFLs have been outweighed by refrigerators, televisions and computers, for which displacement power factors range from 0.5 to 0.9, so in the past controlling CFL power factor has been a secondary issue.

In the "Japanese Top Runner" approach suppliers of all electronic equipment must specify displacement power factor and distortion on the specification plate of each product. All new product models are required to comply with the performance of the best equivalent product on the market at the time.

It is not yet clearly understood what happens to electronic ballasts after many hours of operation. The concern has been raised that if the power electronics inside the ballast are of poor quality and the filtering is based on passive components (especially capacitors) then the power factor could degrade substantially from the original value. A suggested method of guarding against power factor degradation due to ageing would be to insist on a high displacement power factor to begin with, coupled with the introduction of a requirement on power factor maintenance (X% variation after Y% of lamp nominal lifespan). No conclusive evidence yet exists in the public domain that clearly illustrates the ageing effects of different types of electronic ballasts.

In existing legislation, many countries specify a statutory CFL displacement power factor greater than 0.5. No major system problems have been documented. There are many educated opinions[7] as to why this is so including:

- penetration levels have not yet reached high enough levels to cause major problems;
- problems do exist but are difficult to pinpoint and therefore have not been attributed to CFLs; and
- certain power systems are better designed to handle non-linear loads than others.

True power factor cannot be corrected for using traditional power factor correction methods. Instead, the harmonics must be eliminated by means of filtering techniques.

2.5 HARMONICS

Power quality contains two aspects: reliability of supply and voltage quality. Voltage quality is put at risk by deviations from the ideal sinusoidal voltage

[7] From Communications with Network Operator's

caused by a number of factors, including harmonics. Harmonics are becoming a concern as the number of non-linear loads on the system grows.

In an ideal system, voltage and current waveforms are perfectly sinusoidal. However, because of the increasing number of electronic and other non-linear loads, these waveforms can become distorted. This deviation from a perfect sine wave can be represented by harmonics—sinusoidal components having a frequency that is an integer multiple of the fundamental frequency. Therefore, a non-sinusoidal wave has distortion and harmonics. To quantify the distortion, the term total harmonic distortion (THD) is used. The term expresses the distortion as a percentage of the fundamental (pure sine) of voltage and current waveforms.

Increased harmonic levels on the power system can lead to increased resistive losses and voltage stresses. Such effects can sometimes be difficult to pinpoint and can go un-noticed. Other indications that a high harmonic levels exist in a power system include:

- Transformers – harmonics produced by nonlinear loads can cause overheating or the windings and higher eddy currents in the iron core, leading to premature failure. The effects of harmonics on transformer lifespan will be noticed over time as the magnitude of the problem is largely related to the reliability of the transformer and the loading levels. It is often a combination of factors which can lead to transformer failure.

- Conductor overheating.

- Motors are subject to overheating as voltage distortion increases leading to a decrease in efficiency. Harmonics can cause torques which can stall motors, particularly at the 7^{th} harmonic. Malfunctioning of control systems as electronic meters, relays, etc. are matched to the fundamental frequency.

- Overloading on capacitors due to the higher current flowing at higher frequencies, leading to premature ageing.

- Interference with telecommunications and computers. Harmonics produced by high frequency electronic ballasts can cause interference with radio and phone systems. Interference with pilot wire carrier systems may be an issue if harmonics exist at frequencies close to the carrier signal.

- Disturbances in ripple control systems.

- High currents in neutral conductors. The triplen harmonics that are three times a multiple of the fundamental frequency, are additive in the neutral conductor of a 3 phase system.

- Circuit breaker nuisance tripping and fuse mal-operation. Distorted waveforms can cause overcurrent devices to correctly trip, to protect from overheating, even though the load (calculated on the assumption of a pure sinewave supply), would appear to be within the rating of the device. It is not certain if these problems are exacerbated depending upon the network characteristics. It has been suggested that the circulating currents present in mesh networks may make this problem a greater risk.

In New Zealand all electronic equipment with an active input power > 25 W must comply with the harmonic limit standards as specified in AS/NZS 61000:3:2,

Table 3. All electronic equipment with input power <= 25 W can be exempt from meeting the requirements of Table 3 if it can meet an alternative requirement detailed later in this document. In practice there will always be a background level of harmonics created from many sources, including TV's and personal computers.

Recent tests have highlighted a correlation between LPF-CFLs and high harmonic currents.[8] These tests prove that the harmonic performance of the HPF-CFLs that are now readily available is significantly better than their LPF counterparts. These tests considered many how many performance parameters vary with the supply voltage, including the THD and displacement power factor of both HPF-CFLs and LPF-CFLs.

Industrial and commercial customers with a high THD on site are required to take measures to compensate for harmonics, including the installation of harmonic filtering equipment. Power quality problems caused by CFLs dispersed throughout residences will be more difficult to identify and tackle and will raise a debate about who will pay for the expensive filtering equipment.

2.6 IMPROVING POWER QUALITY

The installation of power factor correction capacitors and harmonic filters on the power system are two potential solutions for improving power quality.

Power factor correction capacitors can be used to correct displacement power factor but are not generally effective in reducing harmonic distortion. Harmonic filters specifically designed for this purpose are available.

There are some concerns that should be addressed when employing capacitive compensation or filtering equipment. The presence of non-linear loads on the system cause harmonic currents to flow. Hence the inductive reactance of the system decreases and the capacitive reactance increases as the harmonic order increases. At a given harmonic frequency, there will be a crossover point where the inductive and capacitive reactances are equal. This is called parallel resonance and mostly occurs where there are very high harmonic currents and voltages at the resonant frequency. If this occurs, there will be large harmonic currents circulating between transformer and capacitor. Harmonic resonance can be tackled by adding or removing capacitance from the system or by filtering.

Filtering is generally an effective solution but can also be a costly exercise. In its basic form, a filter consists of a capacitor connected in series with a reactor, tuned to a specific frequency. The impedance of the filter is zero at the tuning frequency, therefore the harmonic current is absorbed by the filter. There are problems which may arise when filters are operating on the power system if they are not strategically placed. When installed onto a system where harmonics are already present, a filter may absorb the existing harmonics on the power system and must be adequately rated as such or will quickly cease to function. A filter will have one or more resonant frequencies where it magnifies the harmonics. Interaction between numerous filters on a supply system may cause troublesome resonances. To install filters onto the power system, detailed system studies are first required to identify the optimum location.

[8] A Comparison of the Philips Tornado CFL with the new High Power Factor Ecobulb – N.R. Watson
Performance of CFLs with Under-voltage – N.R. Watson

There are other means by which the power system can be engineered to withstand high levels of harmonics:

- the size of the neutral conductor may be increased;
- special K-rated transformers may be installed and/or line reactors can be installed at harmonic sources; and
- transformers have also been de-rated in cases where the harmonic distortion levels are higher than 5%.

The New Zealand Electrical Code of Practice "Harmonic Levels" (NZECP 36:1993) and the New Zealand standard AS/NZS 61000:3:2:2003 specifies the maximum harmonic levels that a consumer may generate as seen at the point of common coupling. The maximum permissible THD level is currently set at 5%. Past experience has shown that major problems appear when the THD approaches 5%. There is no equivalent code of practice controlling the power factor of the energy drawn by a consumer's installation. Many lines companies require large customers to correct power factor, if necessary, as a condition of connection.

High THD at a commercial or an industrial site can be identified and controlled relatively quickly and easily. It is the responsibility of the user to control their THD levels. At times, it is adequate to up-rate their transformers and cabling. Otherwise some common solutions include adding motor-generator sets, star-delta transformers or filters on site.

When THD limits are exceeded as a result of residential energy use, NZCEP 36:1993 places the onus on the consumer to take action. However, this has not been enforced in the past and some difficulty would likely arise first identifying the source of the problem and secondly adequately dealing with it. A debate may also arise as to who should meet the cost of this expensive compensation equipment.

There have been some documented cases of CFL use and related power quality implications.

2.7 MAXIMUM PENETRATION

A New Zealand study[9] aimed to estimate how many CFLs per household would cause the THD limit of 5% to be reached. Widely available CFLs, such as Philips PLCE, were assumed to be installed. A model of the South Island 220 kV was used, from the 220 kV bus at Islington to the customer switchboard. The study results indicated that the THD at the point of common coupling (the customer's main switch), reached 5% at a load of 920 20 W CFLs, or 14 lamps per household. The study also concluded that the THD at the point of common coupling is controlled mainly by the impedance of the distribution transformer. The lower the ADMD in the area and the more customers per transformer, the less CFLs it takes to reach the THD limit of 5%.

Lund University Hospital in Sweden has chosen not to use CFLs. Due to the large amount of electronic equipment already on site, they claimed that a large penetration of CFLs would substantially increase the THD in the building. The combined effect of many forms of electronic devices in close proximity can have

[9] Watson

a very significant impact on power quality. Loads which draw high levels of harmonic current can add together and cause a drop in harmonic voltage. This is then imposed onto the customer load at the point of common coupling.

In 1992 Lincoln University[10] was looking at deploying 2500 CFLs on their campus. An experiment was performed to demonstrate the harmonic penetration on the distribution system to ascertain if the New Zealand harmonic limits would be reached. The tests did not consider any other source of harmonics. The results of these tests showed:

- A number much less than the proposed number of CFLs would push the THD well above the 5% limit prescribed in the New Zealand standard AS/NZS 61000.3.2:2003.
- The test results would not have satisfied the equivalent European harmonic standards for either THD or higher harmonic limits. The European standards are more lenient than the New Zealand standards on THD (<8% in Europe) and the lower order harmonics but are more strict than New Zealand on the higher order harmonics allowable.
- If CFLs that met AS3134 were deployed then the voltage distortion would be within limits. AS3134 preceded AS/NZS 61000:3:2. The change was in an effort to harmonize with the international community. In the AS3134 standard equipment with active power input <= 25 W was bound by the harmonic limits of Table 3. There was no alternative requirement available, as is the case with AS/NZS 61000:3:2.2

A case has been documented whereby a road lighting scheme was designed that had 1 MW of total lighting power, to be powered by a 1 MVA transformer. Even though the lamps met the standards laid out in the harmonised European standard EN 61000:3:2, the harmonic currents were so high that the lamps could only be run at 70% full power without overheating the transformer. The causes for this have not been thoroughly investigated.

While it is important to learn from past experience, it is important to consider that harmonic levels on a system largely depend on the power system characteristics. The New Zealand power system is different to the European and American system as it is radial with a relatively high source impedance. A radial system is more susceptible to problems caused by the third harmonic. The European delta wye transformers provide a closed path for third harmonics in the delta winding, thus providing third harmonic isolation between the primary and the secondary. In large numbers, poor quality CFLs may add considerably to the harmonic pollution of a radial system, especially at the third harmonic. Rural distribution systems will also vary greatly from urban systems due to the higher load levels and the capacitive effects of underground cabling that characterise urban systems.

2.8 INTERNATIONAL STANDARDS

The supply utility controls the magnitude of emitted harmonics and there are standards that the manufacturers of equipment and users must comply with.

ANSI (American National Standards Institute) Standard C82 sets a limit of 32% THD for electronic ballast systems and limits the order of all higher amplitude

[10] The Effects of Compact Fluorescent Lamps on Power Quality – N. Watson and S. Hirsch

harmonics to 7% of the fundamental. Many American utilities only include ballasts that have THD of less than 20% in their energy efficiency programs.

At present, the APEC international voluntary standards are being reviewed with a proposal to impose tougher voluntary power factor and harmonic standards. The committee are also endeavouring to develop an international test protocol for CFLs.

The IEC (International Electrotechnical Commission) standards state that lighting equipment must have a PF better than 0.96 and total harmonic distortion (THD) below 33%. However, the IEC lighting standards make an exception for equipment with a rated power of less than 25 W, such as screw-base CFLs.

The latest Australian/New Zealand test method for the emission of harmonic currents for equipment which draws less than 16 Amps per phase is AS/NZS 61000.3.2:2003. This standard superseded the AS3134 standard. CFL bulbs are identified as class C equipment. However a clause in the standard states that class C equipment with input power of less than or equal to 25 watts must instead comply with the requirements of class D, Table 3. Table 3 (Limits for Class D Equipment) 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:

- the harmonic currents shall not exceed the power-related limits of Table 3, column 2, 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 1: Limits for Class D Equipment

Harmonic Order n	Maximum permissible harmonic current per watt (mA/mW)	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	3.85 / n	see standard

Class C equipment with an input power of greater than 25 W must meet stricter higher harmonic limits than those with input power less than 25 W.

By first impression, it appears that Table 1 is more restrictive than the old AS3134 standard. However this is not the case due to the adaptation of the OR clause detailed above.

2.9 EXPERIENCE ELSEWHERE

There have been some countries which have used HPF-CFLs in their initiatives including:

- The Mexican project, Ilumex, employed high power factor and low harmonic distortion CFLs, tested in a laboratory before included in the program. The project was very successful, with the sales goal being reached in five months. No harmonic pollution problems have been recorded. [11]
- Scottish and Southern Energy employed HPF-CFLs in their initiative in the western isles. Diesel generators were being used to meet the peak loads and hence the CFLs were introduced as a peak shaving measure. The rural network has a high percentage of domestic load and there was a fear that LPF-CFLs would contribute to unacceptable harmonics and poor power factor. The scheme was a success and no harmonic problems have been encountered. [12]
- The Electricity Authority of Cyprus specifies a power factor of at least 0.9 for CFLs and a THD of less than 30%.[13]
- The Taiwanese Green Mark Program specifies a power factor of greater than 0.9. [14]

[11] History and Update of Residential Lighting Projects in Mexico – A. Blanc, O. De Burn
[12] Information from Scottish and Southern Energy Ltd.
[13] Electricity Authority of Cyprus – RFQ No. 169/2005
[14] Minimum Energy Performance Standards

3. ECONOMICS OF INSTALLATION

3.1 INTRODUCTION

The economics of installing high power factor CFLs has been examined from both the householder's perspective and from a broader economy wide perspective, in order to capture the costs and benefits. Throughout this analysis, the incremental impact of upgrading from standard power factor bulbs to high power factor bulbs is considered.

3.2 KEY ASSUMPTIONS AND SCENARIOS

The economics were based on the following key assumptions:

- the study case comprises 400,000 households;
- 5 bulbs are replaced per household, resulting in a total replacement of 2 million bulbs; and
- the average power of each bulb being replaced is 85 watts.

Three scenarios were considered:

- Scenario 1 - "Do nothing": i.e. replace the 5 incandescent bulbs with equivalent incandescents;
- Scenario 2 - "Low Power Factor": replace the incandescent bulbs with 5 X 20 Watt 0.5 power factor CFLs; and
- Scenario 3 – "High Power Factor": replace the incandescent bulbs with 5 X 20 W 0.9 power factor CFLs.

When performing the calculations for each scenario, it has been assumed that all five bulbs are switched on for each of 1, 2, 3 and 4 hours ON time in a day.

3.3 COST OF INSTALLATION

It is assumed that a standard CFL costs $6 and that a high power factor CFL costs an extra $0.6.

Therefore for the 400,000 homes in the study area, there is an incremental cost of $1.2 million to install 5 HPF-CFLs per home in preference to LPF-CFLs.

3.4 ELECTRICAL ENERGY SAVED BY CUSTOMER

From the householder's perspective, the key benefit to be gained from the installation of a CFL is reduced electricity consumption and a reduced electricity bill.

The volume of customer energy consumed was calculated for all three scenarios.

A summary of the total volumes of electricity consumed each day by the 400,000 households under the various scenarios is given in the table below.

Table 2: Customer Electricity Consumed per day

Customer Electricity Consumed MWh per day	1 hour ON	2 hours ON	3 hours ON	4 hours ON
Scenario 1 "Do Nothing"	170	340	510	680
Scenario 2 – Low Power Factor	40	80	120	160
Scenario 3 – High Power Factor	40	80	120	160

A summary of the total volumes of electricity saved each day under the various scenarios is given in the table below.

Table 3: Customer Electricity Saved per day

Customer Electricity Saved MWh per day	1 hour ON	2 hours ON	3 hours ON	4 hours ON
Scenario 1 "Do Nothing"	n/a	n/a	n/a	n/a
Scenario 2 – Low Power Factor	130	260	390	520
Scenario 3 – High Power Factor	130	260	390	520

From these results it is possible to conclude that replacement of incandescent bulbs with CFLs results in a substantial energy saving for the customer, down from 85 W to 20 W per bulb. This saving is the same for both the nominal power factor and the high power factor bulbs.

A higher purchase cost of a high power factor bulb does not result in greater energy savings to the consumer.

Over the course of a year, assuming a power price of $0.16 per kWh, this equates to a saving to the household of approximately $4 per bulb (under the 1 hour usage per day scenario). Payback is achieved within 2 years for both types of CFL.

3.5 INCREMENTAL NETWORK CAPACITY SAVINGS

Values of incremental network capacity saved were calculated for all three scenarios. Network capacity savings equate to a reduction in the distribution network capacity required to deliver the required amount of energy to the customer.

The table below shows these savings.

Table 4: Network Capacity Savings

Incremental Network Capacity Savings MVA	1 hour ON	2 hours ON	3 hours ON	4 hours ON
Scenario 1 "Do Nothing"	n/a	n/a	n/a	n/a
Scenario 2 – Low Power Factor	90	180	270	360
Scenario 3 – High Power Factor	126	252	378	504

The above results are based upon 5 bulbs per 400,000 homes, with an average of 85 W per bulb replaced. In the case of the 0.5 PF CFL, 40 VA of network capacity is saved per bulb. This increases to 62 VA per bulb for a 0.9 PF CFL.

From these results it is possible to conclude that the VA demand associated with lighting load is reduced by almost 50% for 0.5 power factor bulbs which means that half of the network capacity that was required for incandescent lighting has been saved and by almost 75% for 0.9 PF bulbs, which means that ¾ of the network capacity that was required for incandescent lighting has been saved.

Importantly, it is difficult to quantify the system heating losses as they are largely dependant on the system parameters (line lengths, types, thicknesses, etc.) and on whether the system is rural or urban. Significant work would be required to clarify the actual parameters of the applicable network.

The current I causes a loss of I^2R in the overhead line, where I = VA/V. Therefore the smaller the value of VA, the smaller system losses will be. The line current would be reduced by almost ½ for a low power factor CFL and by almost ¾ for a high power factor CFL.

These figures are based upon theoretical principles and verification via power system analysis has not yet been carried out. These results serve as a preliminary analysis pending a more in-depth system study.

3.6 ELECTRICITY SAVED/AVOIDED - MARGINAL COST OF GENERATION

In order to determine the marginal value of the electricity savings from the installation of CFLs units, it is appropriate to examine the marginal cost of the alternative generation that might be displaced if the CFLs were installed.

In Parsons Brinckerhoff Associates' report to the Electricity Commission of December 2004, "Thermal & Geothermal Generation Plant Capabilities", an evaluation of the long run marginal cost of all proposed plant in New Zealand was made.

The long run marginal cost of any particular generation technology is influenced by a number of key parameters, including:

- fuel cost;
- scale of project, this influences the capital cost and in some cases will affect the technology choice and efficiency of the operation;
- cost of capital;
- technology of electricity generation and end use. The last ten years has seen a major change in the economics, scale and efficiency of generation technologies;
- time factors, because the long run marginal cost will be determined by the most economic options of the day, some cost factors will change with time and cheaper options will have limited capacity to expand the system; and
- the plant's position in the dispatch order. A generation plant which is designed to operate infrequently to supply peak demands may be economic to install despite higher unit costs. If the dispatch mechanism provides the appropriate economic signal, the average price at which new entry will become economic will be a combination of the long run marginal cost of a mixture of base load, intermediate and peaking plant.

Otahuhu C is a proposed new CCGT power station planned for the Auckland area. This plant is calculated as having a long run marginal cost of $74.6 /MWh.

This can be reasonably assumed to be the marginal value associated with the avoided cost of equivalent electrical energy saved by the installation of CFLs.

The table below summarises the avoided generation (volume and value) in a year.

Table 5: Avoided Generation Volume and Value per annum

	1hour ON	2 hours ON	3 hours ON	4 hours ON
Avoided Generation per annum Volume GWh	47.5	91	143	190
Avoided Generation Value $ million	3.5	6.8	10.7	14.2

3.7 GENERATION INVESTMENT AVOIDED

Installation of CFLs may enable installation of generation to be deferred. For example, installing 2 million CFLs which are simultaneously on for 2 hours per day would be approximately equal to the output from a 91 MW generation plant each year. This would equate to a saving of a peaking plant of capacity 150 MW generating between 1 ½ and 2 hours each day for one year.

The retail cost of installing 2 million CFLs is in the order of $12 million, although it may be possible to negotiate bulk discounts from the supplier.

3.8 IMPACT ON ELECTRICAL PEAK LOAD

This section addresses whether the installation of CFLs in residences could reduce peak loads on the electricity network. Included is an evaluation of household electricity consumption and also an estimate of the reduction in peak demand over a winter weekday based on a number of assumptions.

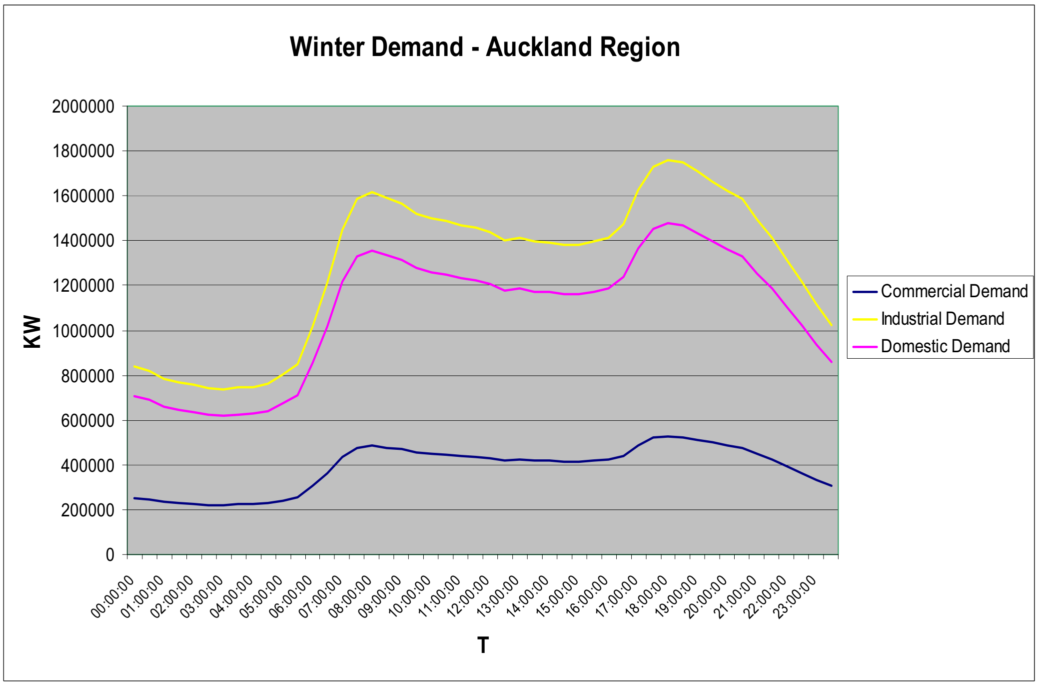
The analysis focuses on the Auckland area. The electricity demand in the Auckland region is forecast to grow at between 2.7% and 3.3% per annum, the fastest growing region in New Zealand.[15] At present, peak electrical demand is approximately 1,900 MW, which is expected to increase by about 60 MW per annum for the next decade.[16]

A number of studies have been performed on possible demand side management techniques suitable for the Auckland area. As residential lighting load makes up a growing percentage of the total peak load, it is believed that large CFL schemes could result in substantial peak energy savings.

[15] Electricity Commission figures February 2005, quoted in Transpower *"Security of Supply into Auckland Review of System Capacity Limitations"*, March 2005
[16] Electricity Commission figures, quoted in *"National Demand Forecast"*

As the Auckland area is a voltage constrained area, introducing more reactive load in the form of CFLs, particularly NPF CFLs, is likely to increase voltage support costs in the area.

Figure 1: Domestic Contribution to Peak Demand



The above demand curves are based upon total regional demand by grid exit point (off take only). Regional definitions are consistent with those used in the 2005 Initial Statement of Opportunities.

Based on assumptions made by SKM[17], the above plot illustrates the various components of demand for a random winter day. Domestic peak load is believed to constitute 54% of the winter evening load, of which roughly 11% can be attributed to lighting load. Based on these assumptions the peak morning residential load would equate to roughly 1,350 MW (or 150 MW lighting load) and the evening peak load equates to just under 1,500 MW (or 165 MW lighting load).

Examining a typical winter weekday, there is a large demand pickup first thing in the morning between 6am and 8am and this can largely be attributed to a pickup in domestic demand as lights, appliances, TV's, radios, etc are turned on. Over the peak period it is assumed:

- There are 5 CFLs installed in 400,000 houses in the region: 1 in the lounge, 2 in the kitchen, 1 in the hallway and 1 in the dining room.
- Over the 2 hour peak period, 2 CFLs are switched on per house simultaneously.
- Each incandescent bulb replaced will be on average 85 W.

[17] Auckland's Electrical Demand Characteristics and Applicability of Demand Management – Sinclair Knight Merz

If you replace an 85W bulb with a 20W bulb there is a savings of 65W per bulb. If you replace two if these in 400,000 houses the total savings will be 65x2x400000 = 52MW for two hours or an energy savings of 104 MWH.

There is a less noticeable demand pickup in the evening from approximately 5pm to 6 pm. As these are the hours of darkness, it is a fair assumption that some of this increase is attributable to residential lighting load. Assuming 1 CFL per 400,000 homes turned on at any one time, the energy savings would be 26 MW over a 1 hour period. Therefore, replacing 5 x 85 W incandescent bulbs is likely to result in a total saving of 130 MWh of energy consumption over the peak periods.

The above estimate of consumption savings does not include savings outside the three hour time window considered. Also this analysis does not include losses which are likely to be at least 10% at the times under consideration.

The results are based upon the aforementioned assumptions and a more detailed analysis could be performed using the HEEP data for lighting load in New Zealand.

A study is also required to assess the impact of CFLs on demand reduction over the summer peaks. While lighting load would not be a large contributing factor to winter peak demand, some demand savings may be possible. The peer review of the monitoring of energy savings for the Mainpower household energy lighting project indicated summer peak savings of 1.49 MW.

3.9 CO_2 ABATED – VOLUME AND VALUE

The reductions in electricity consumption arising from the introduction of CFLs will have a consequential reduction in CO_2 emissions through avoided generation.

In a Concept Consulting report prepared for the NZ Climate Change Office, “Electricity Emission Factor Review” (August 2004), it was estimated that the emission factor was in the range of 600 to 650 tonnes of CO_2 per GWh.

Using an estimated emission factor of 600 tonnes of CO_2 per GWh for the forecast reduced volumes under each scenario would equate to savings as detailed in the table below.

Table 6: CO_2 Savings Volumes

CO_2 Savings tonnes per annum	1 hour ON	2 hours ON	3 hours ON	4 hours ON
Scenario 2 – Low Power Factor	28,500	54,600	85,500	114,000
Scenario 3 – High Power Factor	28,500	54,600	85,500	114,000

The Ministry of the Environment's latest annual inventory of New Zealand's human caused emissions and removals of greenhouse gases indicates that total greenhouse emissions have increased by 22.5% since 1990. The target for New Zealand under the Kyoto first commitment period (2008 to 2012) is to return emissions to 1990 levels.

It has been calculated by the Ministry of Environment that New Zealand will have a net deficit for that first commitment period of 36 million tonnes of CO_2 equivalent (this is the most likely value of the deficit), which equates to 7.2 million tonnes per annum.[18]

The contribution of abated CO_2 from 2 million replacement CFLs used for between 1 and 4 hours a day, would be in the range 28,500 to 114,000 tonnes per annum, or about 0.4% to 1.6% of New Zealand's projected deficit.

According to Point Carbon, the price of a tonne of CO_2 equivalent on the European Emission Trading Scheme as at 27 April 2006 was EUR 16.43. The annual savings are therefore in the order of NZ$900,000 to $3,700,000.

3.10 IMPACT ON INFRASTRUCTURE

Transformers

Non-linear loads on power systems have raised concerns about the potential reduction of the life of a transformer due to an increase in heat losses. The increase in heating experienced by a transformer is dependant upon the harmonic content of the load current and on the design of the transformer.

High harmonic currents inherent in low power factor CFLs pose a number of risks to the transformers operating on the distribution system:

- Extra losses in the transformer core.
- Heating of the windings, reducing the lifespan of the insulation.
- Heating of the conductors, enclosures, bolts, clamps, reducing transformer efficiency.
- Generation of oscillations between the transformer and line capacitances or capacitors.

IEC 60076 Power Transformers states that power transformers should not be expected to carry load currents with harmonic factor in excess of 5% of rating.

It is necessary for a transformer that is expected to supply loads with a high harmonic content be specified with a harmonic current distribution.

Transformer failure due to rich harmonic current waveforms have led transformer manufacturers have developed a rating system called K-FACTOR. This permits the manufacturer to determine the necessary capability of transformers to handle harmonic loads.

[18] Ministry of Environment, quoted on New Zealand Climate Change Office website

It can be difficult to attribute transformer failure to harmonic content as it involves monitoring transformers over a long period of time and failure may depend on a range of causal factors including loading levels. There are an increasing number of non-linear loads now appearing on the power system so the full effects of high harmonic content on transformer lifespan are yet to be witnessed.

Cables

A cable experiences I^2R losses under normal operating conditions. Current distortion introduces additional losses in the conductor. Also the effective resistance of the cable increases with frequency due to the skin effect. Heating losses in cables are a function of frequency, conductor size and conductor spacing. It is sometimes necessary to up-grade cables to account for the harmonic currents that can flow through the conductor.

Motors

Motors and generators can be seriously affected by high harmonic currents resulting in audible noise, oscillating torques (can cause motor stalling) and increased copper and iron losses.

There is an increasing use of variable frequency drives (VFDs) that power electric motors. The voltages and currents from a VFD are rich in harmonic frequency components. Voltage supplied to a motor sets up magnetic fields in the core, which create iron losses in the magnetic frame of the motor. Hysteresis and eddy current losses are part of iron losses that are produced in the core due to the alternating magnetic field. Hysteresis losses are proportional to frequency, and eddy current losses vary as the square of the frequency. Therefore, higher frequency voltage components produce additional losses in the core of AC motors, which in turn, increase the operating temperature of the core and the windings surrounding in the core.

Capacitors

Many power systems have capacitors installed to offset the effect of low power factor and limit the reactive power flowing through the system. Most capacitors are designed to operate at a maximum of 110% of rated voltage and at 135% of their kVar ratings. In a power system characterized by large voltage or current harmonics, these limitations are often exceeded, resulting in capacitor bank failures. Since capacitive reactance is inversely proportional to frequency, unfiltered harmonic currents in the power system find their way into capacitor banks. These banks act like a sink, attracting harmonic currents, thereby becoming overloaded.

A more serious condition, with potential for substantial damage, occurs as a result of harmonic resonance. Harmonic resonance occurs when the inductive and capacitive reactances become equal in an electrical system at a certain frequency. During resonant conditions, increased voltage distortion will result in thermal stress on the capacitors and also on power cables.

Telecoms Systems

Harmonic voltages and currents produce electric and magnetic fields which may impair the performance of communications systems. The magnitude of this disturbance is related to the amplitude and the frequency of the harmonic components. This problem can be alleviated by use of filters or power equipment with low harmonic distortion.

Ripple control systems

New Zealand is unique in that a ripple control system is widely used as a demand side management technique. Ripple control permits remote controlled on/off switching of various loads. Selection of the signal carrier frequency is one of the most important factors in designing a ripple control system. The frequency must be chosen to avoid resonance between network capacitances and inductances. Line companies in New Zealand use audio ripple signals in the frequency range of 110 Hz to 1048 Hz, at roughly 1.1% to 3% of the fundamental voltage[19]. These signals are injected at various voltage levels and appear as inter-harmonics on the distribution system. Any signal having a frequency which is not an integer multiple of the fundamental frequency is termed an inter-harmonic component. Inter-harmonics are placed on the system as voltage signals and cause distortion directly. In extreme cases, this can lead to an attenuation of around 0.6% of the fundamental voltage. Resonances can increase the level of the voltage distortion by as much as 9%.

Both Marlborough Lines and Vector Networks have some ripple control systems which use a 1050 Hz signal.[20] It has been discovered that at 1050 Hz parallel resonance occurs which leads to a number of problems including noise interference and equipment mal-operation. It is planned that the 1050 Hz system will be phased out completely in the future. Orion in Christchurch has noticed problems with signal amplification and flicker when the ripple signal uses a 175 Hz carrier.

Resonances are always present in a system. Changes to the system loads or impedance through system re-configuration, equipment changes or the addition of filters, can cause an existing resonance frequency to shift and coincide with a significant harmonic or inter-harmonic.

Recent testing[21] has shown that the harmonic current content is reasonably high for the bulbs tested at the 5th and 7th harmonics when compared to the fundamental. One brand of bulb has a considerably lower harmonic content than the others tested. However, were these bulbs to be installed in very large quantities, a study may be required to assess the impacts on both the distribution and the transmission network.

Modern ripple control systems are not as susceptible to interference caused by harmonic currents as old legacy systems. However old legacy systems still exist throughout the country, including the North Shore of Auckland, Wanganui, Wairoa, Marlborough, the Hutt Valley and Dunedin. The possibility of unwanted disturbances cannot be ruled out. It has been noted that in the early days of the HVDC link some unwanted behaviour occurred in the ripple control systems within the South Island. Injected harmonics due to the HVDC link was believed to be a large contributing factor to these problems and the replacement of the old technology ripple control systems in the affected areas was initiated as a result.

[19] Fluorescent Light Flicker caused by Load management Signals – Lance Frater, Neville Watson and Joseph Lawrence
[20] Taken from respective Distribution Code's
[21] A Comparison of the Philips Tornado CFL with the new High Power Factor Ecobulb – N.R. Watson

3.11 COST OF POWER FACTOR CORRECTION EQUIPMENT AND HARMONIC FILTERING

The relevant power factor calculation method for the impact of CFLs and other harmonic sources on the transmission network (especially in voltage constrained areas such as Auckland) is the displacement power factor.

Low displacement power factor is generally solved by adding power factor correction capacitors to the distribution system. Power factor correction capacitors supply the necessary reactive portion of power (kVar) for inductive devices. These capacitors can be configured as harmonic filters if necessary, by adding reactors. There are a number of power quality-related concerns that should be considered before capacitors are installed. Potential problems include increased harmonic distortion, including harmonic resonance, and transient overvoltages.

In Section 3.8, the Auckland winter evening peak residential load was estimated to be 930 MW. This equates to a peak residential load of 2.3 kW per house, of which 250 W per house can be attributed to lighting load.

Assuming an average of 85 W per incandescent light bulb, over 3 bulbs are switched on simultaneously over the peak period. For this calculation, it is assumed these 3 incandescent bulbs are replaced with CFLs.

Each residential load class will have a different weighting depending upon its % of the total residential load. It is known that lighting load constitutes around 11% of the total residential load. With incandescent bulbs, the lighting load should have a power factor of close to unity.

If the 3 incandescent bulbs in the household were replaced with nominal power factor CFLs of 0.5 power factor, then the resulting displacement power factor for the household decrease by 0.04 pf.

If the 3 incandescent bulbs in the household were replaced with high power factor CFLs of 0.9 power factor, then the resulting power factor for the household would be 0.01 pf.

To increase the power factor in the household from by 0.03 pf would require 0.109 kVar of capacitive compensation to be installed per kW of household load. Therefore 0.381 kVar of capacitive compensation is required per household to compensate for using a LPF CFL instead of a HPF CFL.

Taking a rough figure of $20/kVar for a compensation capacitor, $7.60 is the cost per household of compensating for the degradation in power factor due to using the nominal power factor bulbs. This figure is independent of voltage.

There are two ways to deal with harmonic problems on the system: system reinforcement or install filtering devices to eliminate the problem. System reinforcement includes increasing the size of the neutral wire, installing K-rated transformers, installing harmonic rated circuit breakers. There are many harmonic suppression devices available including passive harmonic filters, isolation transformers, harmonic suppression systems and active harmonic filters. These types of equipment vary greatly in price, the most effective and expensive being an active filter which can cost roughly $600/kVA. Detailed system studies are required to identify the correct placement of harmonic suppression equipment. The most effective method of dealing with harmonic problems is through prevention.

4. CONCLUSIONS

Market

- There has been some reluctance by users in the past to use high power factor CFLs as poor quality products were released onto the marketplace, with correspondingly low life-spans. However, recent tests performed in New Zealand indicate that the technology is now available to produce superior quality high power factor CFLs.

- With an increasing number of CFLs in the marketplace, suitable product quality standards will be necessary to eliminate poor quality lamps.

Power Quality

- Power quality implications relating to CFLs as a form of residential lighting is not an area which has been studied in detail within the majority of countries. Information in this sector is sparse and difficult to obtain and there are still many unknowns.

- The high harmonic currents inherent in nominal power factor bulbs poses a major primary risk to power distribution companies and system users in terms of a negative effect on power quality.

- Problems caused by harmonic currents and voltages manifest in many different forms and can be difficult to predict and identify, hence making it a tough challenge for the supply companies to pinpoint and tackle the source of the problem once it has occurred. Detailed power systems analysis would be required to ascertain the true magnitude and pinpoint the exact location of the likely increase in harmonic distortion levels.

- Whereas Total Harmonic Distortion (THD) is not currently a major problem in New Zealand, Power Quality (PQ) analysis carried out by distribution companies indicates that harmonic currents are already present on the distribution system.

- It is not clearly understood if a high CFL penetration level would have any adverse effects on ripple control systems. Problems have been noticed when the carrier frequencies of 1050 Hz and 175 Hz have been used. More analysis is required.

- Feedback from network operators indicates that the risk of a disturbance to ripple control systems due to harmonics is worst on radial networks, which is a characteristic of the New Zealand distribution system.

- Recent tests indicate that the harmonic content at the 5^{th} and 7^{th} harmonic order is reasonably high and may cause problems with the ripple control system when implemented in large volumes.

- Harmonic filtering techniques are less than ideal and should be considered as a last resort. Large numbers of dispersed harmonic sources may make it difficult to pinpoint and hence correct the problem. Agreement on what party would be required to meet the expense of such equipment would need to be reached.

Maximum Penetration

- There has been a long term case for high power factor (HPF) and low harmonic content CFLs. However, analysis is not yet available to clearly outline the impacts of low/high levels of penetration of CFLs compared to the impact of other appliances such as televisions and computers.

- It has been proved in Europe that it takes many years to reach market penetration of millions of CFLs, despite heavy promotion and incentives. On the other hand, CFL programs have been popular in New Zealand to date, with 60,500 of the 15 MW and 20 MW energy saving Ecobulbs sold during the 2004 Mainpower South Canterbury Ecobulb HELP project[22]. 200,000 CFLs were installed on the Orion network in Central Canterbury as part of the Central Canterbury energy efficiency lamp pilot program.

Standards

- The current New Zealand standard on harmonics, AS/NZS 61000.3.2:2003, is less stringent than its European counterpart when it comes to the higher harmonic limits allowable.

- It is predicted that tougher power factor and harmonic standards will be proposed for CFLs with the review of the international voluntary standards.

- It is very difficult to make direct comparisons between power systems as harmonic penetration will be totally dependant upon power system characteristics. Therefore, strong consideration should be given to the characteristics of each particular power system and its needs when undertaking the development of or reviewing of specifications.

Economics

- High and low power factor CFLs deliver the same electricity savings to the householder, so there is no incentive on the end user to pay more for a higher power factor CFL.

- Network capacity savings are significantly higher for high power factor CFLs.

- Both types of CFL provide a useful reduction in peak demand.

- Both types of CFL provide a useful reduction in generation requirements and the potential to avoid new generation investment.

- The initial incremental cost of installing HPF-CFLs instead of NPF-CFLs is approximately 10 times less than the cost of capacitive compensation equipment which might become necessary to counteract the degradation in power factor caused by using NPF-CFLs.

CO_2 Emissions

[22] Mainpower HELP Project Data Analysis Report, 16/02/06

- Both types of CFL provide a useful reduction in CO_2 emissions.

5. RECOMMENDATIONS

1. To adopt a preventative approach towards possible power quality problems by:

   - Performing more localised CFL penetration studies on the New Zealand power system, especially in areas of the network susceptible to poor power quality problems and ensuring that the connected equipment will continue to operate as intended in the presence of the pre-determined harmonic distortion.

   - Reviewing and tightening existing standards and guidelines. Given the number of unknowns about the impacts of large numbers of CFLs on power quality and due to the increasing number of non-linear loads on the system, it is recommended that high importance is given to controlling power factor and harmonic distortion, though the review and tightening of existing power quality standards.

   - Agreeing on suitable test protocols to be followed by all manufacturers with respect to power quality. This will eliminate the risk of poor power quality CFLs entering the marketplace, reduce the risk of a monopoly supplier and serve to increase customer satisfaction and CFL usage.

   - Taking the lead on promoting good quality products, assuming the perceived benefits outweigh the costs. Keep in mind that good quality electronic ballasts should be capable of reaching power factors of 0.95 or greater. To consider introducing product guarantees to gain consumer trust and improve consumer satisfaction.

   - Paying close attention to the results of current working groups charged with reviewing international harmonics standards.

2. To adopt a risk management approach in assessing each available option and to perform an assessment of the preventative measures and remedial actions available with each option. I.e. Is it more difficult to prevent and tackle the problem of premature ageing associated with HPF-CFLs or to prevent and tackle the power quality problems associated with NPF-CFLs.

3. Perform research at the household level, to monitor the harmonic levels with or without a large penetration of LPF and HPF CFLs.

4. To consider incentives to overcome the initial high cost of high quality CFLs.

APPENDIX A

References

N.R. Watson, *Performance of Compact Fluorescent Lamps with Under-Voltage*

N.R. Watson, *A Comparison of the Philips Tornado Compact Fluorescent Lamp with the new High Power-Factor Eco-Bulb*

N.R. Watson and Stephen Hirsch, *The Effects of Compact Fluorescent Lamps on Power Quality*

V. Berrutto, P. Bertoldi, *The European Quality Charter for Compact Fluorescent Lamps*

Commission of the European Communities, *C99296EN Ballast Directive*

Concept Consulting, *Electricity Emission Factor Review*

National Lighting Product Information Program, *SREB272*

IAEEL Newsletter 3-4/95, *Power Quality and Lighting*

IAEEL Newsletter 3/94, *China – A Lighting Giant*

Electricity Commission Discussion paper

National Appliance and Equipment Energy Efficiency Program, *Minimum Energy Performance Standards*

Energy Use in New Zealand Households, *Report on the Year 9 Analysis for the Household Energy End-use Project (HEEP)*

Auckland's Electrical Demand Characteristics and Applicability of Demand Management, *SKM, for the Electricity Commission*

Power Quality Effects of CFLs – A Field Study, *Nathan Gothelf*

Impartial Quality Tests of Compact Fluorescent Lamps, *Poul Erik Pedersen*

Mainpower Household Efficient Lighting Project, *Prepared for Mainpower and the Electricity Commission by Energy Mad*

APPENDIX B – SUMMARY OF COSTS/BENEFITS

	Low Power Factor	High Power Factor	Difference HPF-LPF
Cost of Installation per bulb	$6.0	$6.6	$0.6
Total Cost of Installing 2 million bulbs	$12 million	$13.2 million	$1.2 million
Electrical Savings to individual Household per bulb per annum	$4	$4	No difference
Total Electrical Saving over 2 million bulbs households	$8 million	$8 million	No difference
Incremental Network Capacity Savings (VA demand)	50%	75%	HPF 50% greater savings
Avoided Generation Volume/ Value (2 million bulbs 4 hours ON) p.a.	190 GWh $14.2 million	190 GWh $14.2 million	No difference
Impact on Electrical Peak Load	161 MW saving	161 MW saving	No difference
CO_2 saving - (2 million bulbs 4 hours ON) tonnes per annum	114,000	114,000	No difference
Impact on Infrastructure			Not quantified
Power Factor Correction and Harmonic Filtering			To bring the LPF up to HPF costs c.$7.60 per household $3 million for 400,000 households Harmonic filtering roughly $600/kVA