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The modern domestic load and its impact on the electricity distribution network

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THE MODERN DOMESTIC LOAD AND ITS IMPACT ON THE ELECTRICITY DISTRIBUTION NETWORK

A thesis submitted in fulfilment of the requirements for the award of the degree

Master of Engineering - Research

From

UNIVERSITY OF WOLLONGONG

by

Sean Toby Elphick, B.E. (Elec) (Hons)

School of Electrical, Computer and Telecommunications Engineering

2011
I, Sean Toby Elphick, declare that this thesis, submitted in fulfilment of the requirements for the award of Master of Engineering - Research, in the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Sean Elphick

September 2011
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<tr>
<td>CFL</td>
<td>Compact Fluorescent Lamp</td>
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<tr>
<td>HV</td>
<td>High Voltage (&gt;132 kV)</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage (&lt; 1000 V)</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage (1000 V – 132 kV)</td>
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<tr>
<td>PQ</td>
<td>Power Quality</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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ABSTRACT

Modern domestic loads are considerably different to those found in households 10 to 15 years ago. In addition to traditional heating, cooking and refrigeration loads, modern loads are likely to include a variety of sophisticated devices containing power electronic front ends. Such front ends can lead to a range of power quality (PQ) impacts on the electricity network, primarily harmonic distortion. Indications are that penetration levels of non-linear residential load are likely to increase. The decision by the Australian Federal Government to ban the sale of traditional incandescent light globes by 2010 is one driver of the increase in non-linear load. At present, the only viable alternative to the incandescent light globe is the compact fluorescent lamp (CFL), a well-known non-linear load.

The evolution of the residential load in terms of magnitude and characteristics into a significant distorting load and as such a potential source of significant power quality disturbances is worthy of detailed study. Distribution utilities are required by law to maintain acceptable power quality levels on their distribution networks to ensure safe and reliable operation of the network as well as equipment connected thereto. This is only possible if detailed understanding of the behaviour of equipment connected to the distribution network has been achieved so that proper planning schemes can be put in place.

In order to understand the electrical behaviour of modern loads the electrical performance of a range of appliances, including a range of CFLs, was examined through laboratory investigations. Examination was made of performance under a range of input voltage conditions (magnitude and waveform distortion). A realistic low voltage (LV) electricity distribution network simulation model was developed to assess their impact on distribution system PQ levels using the appliance load characteristics determined through laboratory testing. This flexible distribution system model allowed a range of feeder lengths and loading scenarios to be examined.
Field monitoring conducted in conjunction with theoretical work is used to substantiate the simulation studies. Broadly, the majority of the results obtained from the modelling work were found to be indicative of credible harmonic magnitudes and profiles. Results most reflective of recent field observations were obtained using the simulation models where the injected current levels were based on appliance behaviour when such appliances were supplied with distorted input voltages rather than sinusoidal input voltages. There are a number of reasons that make direct comparison of model outputs with field data very difficult. Notwithstanding these difficulties, good correlation between field measurements and model outputs was achieved for $3^{rd}$ and $5^{th}$ harmonic voltage levels. Correlation between model outputs and field data for the higher order harmonics which were examined ($7^{th}$, $15^{th}$ and $21^{st}$) was not as strong.

On the whole, results obtained from the simulation models indicate that a very high penetration of modern domestic appliances (i.e. large numbers in each residence) will result in harmonic voltage levels that will exceed the Australian harmonic voltage planning levels on LV feeders. The modelling also indicated that the profile of the harmonic voltages due to modern domestic appliances may be different to the traditional profile where low order harmonics dominate. There is evidence to show that if high penetration of modern appliances occurs, the dominant voltage harmonics due to interaction of appliance load currents with network impedance may be the $7^{th}$ or $15^{th}$ harmonic. Special emphasis has been placed on the impact of CFLs on harmonic levels. Results of modelling clearly show that a large number of CFLs can have a significant impact on voltage harmonic levels.

It was clear that some of the simulation models which were developed produced values which were unlikely to be representative of those seen in practice and this is an avenue for future research. Methods of harmonic modelling are complex, especially for higher order harmonics, and if very accurate models are required, some of the assumptions used may need closer examination. Further, as appliances develop over time, it may be necessary to periodically perform studies such as the one presented in this thesis in order to maintain a complete understanding of the electrical behaviour both of modern loads and the LV distribution network.
ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisors, Dr Phil Ciufo and Associate Professor Sarath Perera for their hours of assistance, mentoring and encouragement both during this project and throughout my career in general. Their passion for engineering and teaching are a credit to themselves and is contagious to any student truly interested in engineering.

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Finally, I’d like to thank my wife Katherine along with the rest of my family whose support I have been able to count on throughout this project and in my life in general.
CHAPTER 1 : INTRODUCTION

1.1 Evolution of the Modern Domestic Load

Residential electricity consumption accounted for 28% of the total electricity consumption in Australia in 2007 [1]. Studies commissioned by the NSW Government show that residential electricity consumption in NSW increased by 22% in the decade 1994 - 2004 [2]. Although electricity consumption would be expected to increase with population growth, the notable aspect is that the average electricity consumption per capita and per household has increased. The modern residential load is considerably different to that seen 10 to 15 years ago. It is clear that it has grown significantly in consumption and also in characteristics. In addition to traditional resistive heating/cooking loads and refrigeration loads, the average modern residential load is now likely to contain a variety of sophisticated devices mostly powered and controlled through power electronic systems which were rarely seen a decade ago. Such devices are non-linear loads which may have a range of negative power quality impacts on the electricity network. Primarily these are harmonic distortion but other impacts can include deterioration of power factor. The trend towards greater levels of residential non-linear loads is likely to increase with the adoption of large screen televisions and home theatre systems that are rated at power levels significantly higher than their predecessors. These devices also contribute to a significant non-linear standby power load, something relatively unheard of a decade ago. Air conditioner penetration is also expected to increase. Modern air conditioning units are now quite large (up to several kW for single phase units and 14 kW for ducted 3 phase units) and are now almost exclusively powered by variable speed drive systems which are a well-known non-linear load.

In 2007, the Australian Federal Government announced that certain inefficient general purpose incandescent light globes would be phased out between 2009 and 2010 [3]. Although LED lighting technology is maturing, at present, the only viable alternative to the incandescent light globe is the compact fluorescent lamp (CFL). The CFL is a well-known non-linear load [4]. Various sources [5], [6] state that lighting load accounts for 9% of the household electricity usage in NSW and
although significant energy savings will be achieved through the use of CFLs it may be at the cost of increased power quality problems.

The evolution of the residential load, in terms of magnitude and characteristics, into a significant distorting load and a potential source of power quality issues is worthy of detailed study. According to [5], up to 69% of the modern domestic load may now be comprised of non-linear loads. The effects of harmonic distortion caused by non-linear devices on the distribution network and equipment connected to it can be varied and may be subtle, only becoming apparent over many years.

Distribution utilities are required by law to maintain acceptable power quality levels on their distribution networks to ensure safe and reliable operation of the network as well as equipment connected thereto. While each state in which an electricity distribution company operates in Australia may have their own specific harmonic limits, universal limits for harmonic distortion which must be met by all electricity suppliers are outlined in the National Electricity Rules (NER) [7] which have jurisdiction across Australia.

In order to comply with the applicable harmonic limits, utilities need to understand the electrical operating characteristics of equipment connected to the electricity network. It appears that few studies have been completed to characterise the power quality performance of modern loads and/or to assess the impact of the modern domestic load on distribution system harmonic distortion levels. Those studies that have been completed are now dated and generally apply to North American networks. The design and construction of Australian distribution networks is significantly different to that of North American networks. There does not appear to be any studies specifically related to the Australian case.

No studies exist that quantify the effect of a high penetration of CFL lighting. This load cannot be ignored as is a source of harmonics in combination with other loads. Thus, it is evident that there is a need for a thorough study to characterise and assess the power quality impact of the modern residential loads on the electricity network. Such a study will facilitate a better understanding of the power quality behaviour of
the modern domestic load and should allow electricity distribution utilities to make informed power quality planning decisions based on this behaviour.

1.2 Harmonic Distortion

The effects of harmonic voltages and currents on the distribution system and equipment connected thereto vary and can be subtle and may only become apparent over a period of time.

For distribution systems, the effects of harmonic voltages and currents include:

- Additional losses in the distribution system caused by the need to supply non-useful harmonic current.
- Higher than expected currents for which distribution system equipment must be rated.
- Additional eddy current losses in transformer windings and core.
- Dielectric losses and overheating of network capacitors which may lead to premature failure.
- Resonance at harmonic frequencies. This leads to very high harmonic voltages and currents.
- In some cases, excessive harmonic levels can interfere with ripple injection control signals used by distribution utilities to control loads such as street lighting and off peak hot water systems.

The effects of harmonics on customer equipment connected to the distribution network can be subtle. In general, harmonics will not immediately damage or destroy equipment unless a resonance condition is encountered. The following are some of the impacts of excessive harmonic voltage levels on equipment connected to the distribution network:

- Additional heating and loss of life in equipment such as induction motors.
- Higher than expected currents that can have thermal impacts on equipment.
- Interference with communication equipment.
Maloperation of equipment which relies on waveform zero crossings.
Higher than expected voltage levels for which equipment must be rated.
Audible noise through speaker systems and vibration of laminations in equipment such as ceiling fans.

1.3 Aims of the Thesis

The past decade has seen major changes to the appliances which comprise the domestic load. Appliances which may have been considered to be passive loads now have power supplies which consist of power electronic systems which can lead to power quality disturbances, predominately harmonic currents. Equipment impacts the electricity network through the current that it draws. While examinations have been made of the input current characteristics of first generation electronic appliances, there is little literature dealing with the performance of more modern loads. Understanding the input current characteristics of modern loads is essential if accurate understanding of the performance and potential power quality impacts of modern equipment connected to the power system is to be developed.

The aims of this thesis are to characterise the input current behaviour of modern domestic appliances and to assess the potential power quality impacts of the modern domestic load on the electricity distribution network. Special emphasis is placed on the impact of high penetration levels of CFLs on network harmonic levels. This is due to the fact that CFLs are a load which has recently experienced, and will continue to experience very large increases in penetration levels. A number of common modern appliances are tested with operating characteristics assessed under varying input voltage conditions. These include voltage levels at the upper and lower ends of the Australian LV voltage range and a number of distorted input voltage conditions.

The results obtained in this study will provide electricity distribution network service providers with a comprehensive indication of the power quality ‘footprint’ of the typical modern domestic load. This includes the characteristics of individual appliances as well as an understanding of the broader impact of the load when appliances are operating together. This information can then be used in a range of
applications, particularly in network planning, to ensure harmonic distortion levels are maintained within applicable standards. The results obtained in this thesis will also be of use to equipment manufacturers as such results will indicate the power quality environment in which modern devices are expected to operate correctly.

1.4 Scope and Methodology

This study is an investigation of the input current characteristics and the impact that this current will have on the electricity distribution network. For the purposes of this study, the effect of domestic loads on electricity distribution network power quality is confined to the power quality disturbance most commonly associated with the devices that now make up the modern domestic load; harmonic distortion.

The domestic load to be considered will consist of a number of typical appliances. Unusual appliances or those unlikely to be found in most domestic loads will not be considered in this study. The composition of the domestic load under study is discussed in Chapter 5.

Assessment of the impact of the modern domestic load on electricity distribution system harmonic distortion levels will be undertaken in three stages;

Stage 1: Characterisation of the Electrical Performance of Domestic Loads

This stage involves laboratory testing of a range of domestic appliances in the laboratory. These tests are performed to examine the input current characteristics of the domestic appliances over the range of operating conditions and influence factors likely to be seen on a typical electricity distribution network. These influence factors include variation in supply voltage magnitude and background supply voltage harmonic distortion.

Stage 2: Modelling and Simulation

The input current characteristics of the modern domestic appliances obtained in Stage 1 are incorporated into network models to determine the impact of the modern
domestic load on electricity distribution network harmonic distortion levels. Modelling is restricted to the low voltage network extending as far as the medium voltage/low voltage distribution transformer. A range of scenarios are developed to take into account the range of distribution network loading levels and other operating characteristics. In all cases, data for models has been obtained from Endeavour (formerly Integral) Energy, an electricity distribution company operating in NSW, Australia.

**Stage 3: Verification of Models**

Previously collected data such as that incorporated in the Long Term National Power Quality Survey (LTNPQS) [8] as well as other studies will be utilised in conjunction with network data specifically collected for this project to verify the performance of the models against practical network performance.

**1.5 Original Contributions of this Thesis**

The original contributions made through the work presented in this thesis are as follows:

1. A review of the literature related to the performance of modern domestic appliances and their potential impacts on power quality has been carried out. Some of the shortcomings identified in this literature have been addressed by new work performed in this thesis.

2. A comprehensive understanding of the input current characteristics of a range of common modern domestics appliances. While a considerable collection of literature is available detailing the electrical characteristics of the “first generation” of many of the appliances tested, little data is available for the most modern devices. It is clear that some appliances perform better than their predecessors.

3. A comprehensive understanding of the input current characteristics of modern CFL lighting. This includes assessment of the impact of varying input voltage
conditions. It is readily apparent that a number of CFL brands available in Australia do not comply with the Australian standard for equipment harmonic emissions, AS/NZS61000.3.2:2007 [9]

4. An understanding of the potential impacts of modern domestic appliances on distribution system harmonics levels has been developed.

5. Developments have been made in the understanding of the impact of CFLs on distribution system power quality levels. The impact of the greatly increased penetration of these devices has been a major source of interest to the electricity supply industry. It is clear that many CFLs have operating characteristics different to that of other appliances. It is also apparent that several CFLs operating together have the potential to be the largest harmonic producing load in a domestic residence.

6. A flexible and relatively easy to implement method of network and load modelling has been developed to aid in the assessment of the impact of modern appliances on distribution low voltage network harmonic levels. Model outputs correlate well with field data for low order harmonics.

7. Field monitoring has provided an indication of harmonic levels at various locations on low voltage feeders. While considerable data is available for harmonic levels close to distribution substations (transformers) little data is available for locations remote of the substation (i.e. at the end of LV feeder runs). The data collected as part of this project will aid in understanding the profile of harmonic levels along low voltage feeders.

1.6 Publications Related to this Thesis

The following publications have arisen as a result of the work presented in this thesis:


1.7 Structure of the Thesis

The structure of the thesis is described below:

Chapter 2: Literature review - This chapter reviews studies which have been undertaken nationally and internationally to attempt to determine the power quality characteristics and impacts of domestic loads on the electricity distribution network. The vast majority of the literature examines the potential harmonic impacts of domestic loads on the electricity distribution network. To begin, a description of the modern domestic load and its development, including changes in overall demand and characteristics is given. Following this, literature relating to the potential power quality impacts of common domestic appliances on the electricity distribution network is reviewed. Special emphasis has been placed on the CFL as this is a load type which will experience significant growth in the near future.
Chapter 3: Electrical Performance and Characteristics of the Modern Compact Fluorescent Lamp (CFL) - This chapter addresses the shortage of concise information with regard to the electrical performance and characteristics of the modern domestic CFL. This is achieved by a laboratory testing regime designed and conducted to identify the electrical performance and characteristics of modern domestic CFLs over a range of influence factors likely to be present on Australian distribution networks. A range of CFL brands and construction types purchased from common retail outlets have been subject to this testing regime. Thorough understanding of the modern CFL is critical as lighting load is a significant part of domestic load and the results obtained in this chapter will be used in the construction of the domestic load models to be utilised in subsequent chapters of the thesis.

Chapter 4: Electrical Performance and Characteristics of Other Modern Domestic Appliances - This chapter explores the electrical performance of modern domestic loads other than CFLs which was given special examination in the previous chapter. Performance characteristics examined include power consumption and power quality performance. This is achieved through a series of laboratory tests designed to assess the characteristics of loads over a range of operating conditions. The results from the testing described in this chapter have been used to develop a domestic load model which can be utilised to quantify the impact of the domestic load examined on distribution network power quality.

Chapter 5: Modelling Methodology for Simulation of the Impact of the Modern Domestic Load on Electricity Distribution Network Harmonic Levels – This chapter details the modelling methodology which has been developed to examine the impact of modern domestic loads on low voltage electricity distribution network harmonic voltage levels. Using the data obtained from laboratory testing of appliances described in the preceding two chapters, load models have been developed for the domestic appliances of interest. These models are then used in conjunction with low voltage feeder models to produce a flexible simulation model of the load and network. Harmonic levels for a range of network and loading scenarios may then be observed.
Chapter 6: Simulation Outputs - This chapter presents the outputs of the network simulation models described in the previous chapter. These models have been developed to investigate the impact of the modern domestic load on low voltage distribution system harmonic voltage levels. Particular attention is paid to the impact of CFLs which are a load which has recently had rapidly increasing penetration levels and, in some cases, has a harmonic profile atypical of other low voltage appliances.

Chapter 7: Comparison between Simulation Outputs and Field Measurements - This chapter compares the outputs of the simulation models with data measurements from a number of sites in the field.

Chapter 8: Conclusions – This chapter summarises the important findings from the work presented in this thesis. Limitations of the study and avenues for further work are also outlined.
CHAPTER 2 : LITERATURE REVIEW: POTENTIAL POWER QUALITY IMPACTS OF THE DOMESTIC LOAD ON ELECTRICITY DISTRIBUTION SYSTEMS

2.1 Introduction

The past decade has seen considerable changes in the domestic load in terms of demand and appliance electrical characteristics. The result of these changes is that the modern domestic load now has the potential to have a significant impact on distribution network power quality levels. From a power quality viewpoint, the most important evolution in the domestic load has been the proliferation of single phase devices powered by switch mode power supplies or other power electronic systems. An increasingly dominant load is the modern air conditioner. These are also supplied by power electronic inverters, whether they are single-phase, or three-phase units. Another major change to the characteristics of the domestic load has been precipitated by the Australian Federal Government policy to ban incandescent light globes. In the short term this will lead to a significantly increased penetration of compact fluorescent lamps (CFLs), a non-linear load, and the only currently viable alternative to traditional incandescent globes. It is clear that the modern domestic load now comprises a significant proportion of non-linear devices which have the potential to lead to adverse power quality impacts on the electricity distribution network.

This chapter reviews studies which have been undertaken nationally and internationally that attempt to determine the power quality characteristics and impacts of domestic loads on the electricity distribution network. To begin, a description of the modern domestic load and its development, including changes in size and prominent features is given. Following this, literature relating to the potential power quality impacts of common domestic appliances on the electricity distribution network is reviewed. This literature review is limited to the impact of the modern domestic load on the harmonic distortion levels.

The literature review is confined to typical domestic loads; those likely to be found in most domestic installations. Special emphasis has been placed on the CFL as this
is a load type which will experience significant growth in the near future. A detailed study has been undertaken of the literature describing the electrical properties of the modern CFL. This precedes the examination of the potential impacts of CFLs on harmonic distortion levels.

There is a large collection of literature detailing the harmonic behaviour and the potential impact on the electricity distribution network of specific harmonic sources, such as televisions and inverter driven air conditioners. However, few of these examine the potential impacts of a number of such loads interacting together. Of particular interest for this study is literature related to the CFL lighting. Although the CFL has been in existence since the 1980s, it is only in the first decade of the 21st century that penetration levels have begun to increase rapidly. This is the result of a range of political and social pressures being exerted in an attempt to increase energy efficiency. There are two main types of studies which have been conducted on the CFL; those that attempt to characterise the electrical properties of the CFL and those that attempt to determine the effect of widespread CFL installation on the electricity distribution network. The literature pertaining to both types of studies is reviewed in this chapter.

2.2 Composition of the Australian Modern Domestic Load

2.2.1 Basic Composition

Residential electricity consumption accounts for 27.8% of the total electricity consumption in Australia [1]. While there have been significant changes to the domestic load due to technological advances, the modern domestic load still contains many of the traditional appliances seen a decade ago. Hot water heating still represents the major domestic load and accounts for up to 40% of domestic energy use [2]. Cooking and space heating also account for significant level of domestic energy use as does refrigeration. As of 2005, 99.9% of domestic residences had refrigerators [10], while 50% had air conditioners [2]. 2008 figures available in [11] put air conditioner penetration at 65%. The main differences between the modern domestic load and that of a decade ago are the penetration and characteristics of
electronic appliances such as computing and audio-visual loads, air conditioners and CFLs.

Figure 2.1 shows a pie chart of the composition of the modern domestic load from [5].

![Breakdown of Household Electricity Use, NSW, 2000](image)

**Figure 2.1: Composition of Modern Domestic Load [5]**

Figure 2.2 illustrates another domestic load energy use breakdown [6]. The data in Figure 2.2 generally agrees with the data presented in Figure 2.1. It should be noted that Figure 2.2 includes all energy use and not just electrical energy.
2.2.2 Lighting Load

The decision taken by the Australian Federal Government to ban the use of traditional incandescent light globes by 2010 will see a dramatic change in the composition of domestic lighting load. Although LED technology is maturing, the only viable alternative to the incandescent light globe at present is the CFL. The CFL is well known as a non-linear load [12], [13]. According to [5], lighting makes up 9% of the household electricity usage in NSW. Although significant energy saving will be achieved through the use of CFLs it may be at the cost of increased power quality problems. The potential power quality impact on the electricity distribution network of installing millions of CFLs is yet to be fully investigated.

2.2.3 Standby Power

Many modern appliances have ‘standby power modes’ that were rarely found a decade ago. The Australian Greenhouse Office now estimates that standby power accounts for 10% of residential household electricity usage [2]. In fact, although energy efficiency gains have been made to many appliances during normal operation, their use of standby power during non-operational periods has in some cases made
them less energy efficient than their predecessors [2]. In almost all cases, standby power will be consumed by switch mode power supplies.

2.2.4 Electronic Appliances

The modern domestic load now contains a variety of devices with disparate input current characteristics and can be expected to contain a range of electronic equipment powered by switch mode power supplies, such as computer equipment and audio-visual appliances, along with more traditional loads. For example, according to [2], the proportion of homes with computers, air conditioning and clothes dryers for an electricity distribution area in NSW has grown by 32%, 21% and 12% respectively over the last decade up to 2004. It is stated in [14] that in 1992 air conditioner penetration in Australian households was 24.7% while personal computer penetration did not even rate a mention. The study presented in [2] states that the air conditioning market has grown at approximately 40% per annum since 1991 and [11] puts air conditioner penetration at 65% of residences. This agrees well with [15] which states that as of 2006 52% of NSW homes use air conditioning for cooling, while 71% of homes in WA use air conditioning or evaporative cooling [16]. Modern air conditioning units are now quite large, up to approximately 5 kW or greater for single phase split systems and approximately 14 kW for ducted three-phase units. Even the smallest single phase split system is generally of the order of 3 kW. Almost all modern air conditioning systems consist of variable speed drive systems which are a well-known non-linear load. Data presented in [10] puts computer penetration at 68% of residences as of 2005, while [11] puts PC penetration in 2008 at 87%.

The adoption of large screen televisions and home theatre systems is expected to continue. Figures as of 2008 available in [11] now show television ownership of 1.5 units per household and DVD player penetration of 72%. By 2010 LCD type televisions are expected to account for 70% of televisions sold. As of 2006, the average screen size for an LCD television was 73 cm. These modern devices are rated at power levels significantly higher than their predecessors and indications are that power ratings and also hours of operation per annum are increasing.
2.2.5 Growth of the Domestic Load

According to [2], residential electricity consumption in NSW increased by 22% in the last decade up to 2004. According to [11], electricity consumption will grow at 4% per annum until 2020. Although total electricity consumption would be expected to increase with population growth, the average electricity consumption per capita and per household has also increased. This is despite improvements in the technology and energy efficiency of appliances, improved energy efficiency of residences and a tendency towards smaller households (in terms of occupants per dwelling).

It is stated in [2] that several interrelated factors are believed to be driving increased consumption within the residential sector. These include:

- Population growth
- Poor planning of residential areas and design of individual homes, which exacerbate climatic problems and reliance on air conditioning
- Increased uptake of appliances to improve amenity
- Energy pattern usage of appliances, in particular standby power
- The relative affordability of electricity compared with other energy sources

Table 2.1 documents the penetration levels of selected appliances between 1994 and 2005.
Table 2.1: Penetration Levels for Selected Appliances [10]

<table>
<thead>
<tr>
<th>Appliance</th>
<th>1994 (%)</th>
<th>1999 (%)</th>
<th>2002 (%)</th>
<th>2005 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>99.7</td>
<td>99.7</td>
<td>99.9</td>
<td>99.9</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>94.2</td>
<td>94.7</td>
<td>95.2</td>
<td>96.4</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>51.7</td>
<td>53</td>
<td>55.4</td>
<td>55.1</td>
</tr>
<tr>
<td>Separate Freezer</td>
<td>44.9</td>
<td>40.1</td>
<td>38</td>
<td>36.9</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>25.1</td>
<td>30.1</td>
<td>34.7</td>
<td>41.5</td>
</tr>
<tr>
<td>Television</td>
<td>na</td>
<td>98.9</td>
<td>99.2</td>
<td>98.5</td>
</tr>
<tr>
<td>Vacuum Cleaner</td>
<td>na</td>
<td>95.2</td>
<td>95.5</td>
<td>95.2</td>
</tr>
<tr>
<td>Microwave</td>
<td>na</td>
<td>82.9</td>
<td>87.3</td>
<td>90.6</td>
</tr>
<tr>
<td>Computer</td>
<td>na</td>
<td>44.8</td>
<td>59.8</td>
<td>67.8</td>
</tr>
</tbody>
</table>

Table 2.1 clearly shows strong growth in electronic appliances such as microwaves and computers.

The development of the domestic load into one containing a significant number of non-linear loads may have a range of negative power quality impacts on the electricity network, primarily harmonic distortion. For large air conditioning systems, power quality problems can include flicker, short voltage dips on compressor start-up and unbalance issues due to the large single phase load. Based on the data in Figures 2.1 and 2.2, 43 – 69% of the domestic load could be comprised of electronic devices which are non-linear loads.

2.3 Impact of Domestic Loads on Power Distribution System Harmonic Distortion Levels

Distorted currents drawn by non-linear loads interact with network impedances to produce distorted voltages. 43 – 69% of the modern domestic load may now be considered to be non-linear and will draw harmonic currents. High levels of harmonic distortion are undesirable and can have varied impacts on the electricity distribution network and equipment connected thereto as discussed in Section 1.2.

There are several studies which examine the potential harmonic distortion impacts of specific appliances on the electricity distribution network. These appliances include
televisions and variable speed (inverter driven) air conditioners. The studies
generally treat the specific load as the only source of power quality disturbances. The
remainder of the load is modelled as linear; a simplification as this is obviously not
the case in practice. There are fewer studies which examine combinations of non-
linear domestic loads as would be the case in the real world.

2.3.1 Television Loads

Television load

Televisions are a well-known non-linear load found within the vast majority of
domestic loads. Studies presented in [17], [18] and [19] clearly show that very high
penetration of televisions switched on during sporting events have the potential to
raise harmonic voltage levels, particularly 5th harmonic levels, on the electricity
network. The study presented in [17] contains data from a Brazilian electricity
network, while [18] contains data from an Australian and a Brazilian electricity
network.

Sporting events present an opportunity to study the effect of single phase electronic
loads on the electricity distribution network since during these events, there is a
much higher number of televisions operating in ‘on’ mode (i.e. not on standby) than
would normally be the case. This is particularly the case if the sporting event is being
screened at an unusual time, such as in the early morning, when there is generally a
minimum of load on the electricity distribution system.

In [17], the increases in harmonic voltage levels during the sporting event were
observed at transmission level and thus have the potential to impact on a very large
number of loads connected to the electricity distribution network. For the Australian
case, as discussed in [18], increases in harmonic voltage levels were observed up to
the medium voltage level.

The effect on harmonic levels due to higher than normal penetration of televisions
operating in ‘on’ mode on the Australian electricity network is detailed in [18]. In
this study the impact of the televisions was not as obvious as those seen for the
Brazilian electricity network. It is postulated that this is due to most modern
television sets now consuming standby power at all times. Thus the increase in harmonic
levels when large numbers of televisions are operating is less pronounced as a basic level of harmonics is always present due to the standby power. Standby power now accounts for a significant proportion of energy use in residential homes. Data presented in [6] puts this figure at 4% of total energy use, while [18] states that it is 10%. According to [18] no studies have been carried out to assess the implications of harmonics generated due to standby modes of operation of appliances.

While sporting events provide an excellent opportunity to assess the impact of very high penetration of electronic devices on harmonic levels, it also presents an atypical loading level on the network. Consequently it is difficult to use the studies in [17] and [18] to make judgements related to the impact of electronic devices such as televisions on distribution power quality levels under more typical operating conditions.

2.3.2 Variable Speed Air-conditioning Load

Variable speed (inverter) type air conditioners were identified in the early 1990s as a load that had potential to affect distribution network power quality levels [20]. Air conditioners have received special attention because they constitute a large load compared to many of the other domestic appliances.

Both the size and number of inverter driven air conditioners have grown substantially over the past decade. According to [2], the proportion of homes with electric air conditioning has grown by 32% in the decade 1994 to 2004. Penetration levels in some areas are in excess of 100%. Modern split system or ducted air conditioners range in size from approximately 2 kW up to approximately 14 kW and are almost universally inverter driven as these units are more efficient than traditional types.

There are several studies which specifically investigate the potential impacts of increased penetration of variable speed air conditioners on the electricity network [20], (1992), and [4], (1994), present simulation studies of the impact of variable speed air conditioners on harmonic levels on residential power systems. Both modelling studies are related to North American distribution systems. The results of the studies generally agree that high penetration of variable speed air conditioners
will cause excessive voltage distortion and will drive voltage THD levels above the IEEE limit of 5%.

In [20], two types of variable speed air conditioners are considered; filtered and unfiltered. The study finds that 60% penetration of filtered air conditioners on a given feeder will result in voltage THD levels above 5%. For unfiltered units, penetration reduces to 20% in order to maintain voltage THD levels below 5%. A modelling exercise presented in [4] finds that the 5% voltage THD limit will be exceeded at the service entrance to residential homes if the penetration of variable speed air conditioners on the lateral modelled increases to 33%. Further, it was found that if 9% of homes on a modelled 12.47 kV distribution feeder were to install variable speed air conditioning, the voltage THD would exceed the 5% limit.

Both [4] and [20] make a major assumption in the methodology used to perform the modelling. The assumption made is that the variable speed air conditioner is the only non-linear load on the modelled networks and hence the only source of harmonics. This removes the possibility of harmonic addition or cancellation due to the interaction between harmonic currents drawn by the air conditioners and harmonic currents due to other non-linear loads. The harmonic currents due to each air conditioner are also assumed to add arithmetically. The possibility that the harmonics from different brands of air conditioner employing different power electronic front end designs may cancel is not taken into account. The validity of these assumptions is called into question by the results presented in [21]. The study presents a statistical summation of the harmonic currents produced by a large number of variable speed air conditioners. The study investigates the impact of three specific designs of rectifier front ends for variable speed air conditioners and how they interact with each other and the electricity distribution network. The study finds that phase cancellation between a large number of the three different rectifier designs can decrease current distortion levels. This study also simulated a North American distribution system. The simulation included seven overhead distribution feeders servicing 40 MW of load with 42 miles of 12.5 kV feeders and 27 miles of 25 kV feeders. Harmonic distortion due to other loads was also considered in the study. The study found that for the simulated network, the penetration of variable speed air
conditioners would need to be kept below 7% for one rectifier design, below 5% for another design and below 4% for a third design to prevent the 5% voltage THD limit being exceeded. The air conditioner penetration levels that resulted in the THD limit being reached are significantly lower than the penetration levels seen in [4] and [20] clearly indicating that the effects of harmonic currents due to other loads cannot be neglected.

Although the study presented in [21] is an improvement on the studies in [4] and [20] since it takes into account the effects of different rectifier designs as well as harmonics due to other loads, because all of the aforementioned studies are performed on North American networks their relevance to the Australian case are limited. North American electricity distribution networks are considerably different to Australian networks in terms of voltage level (110 V low voltage system), transformer numbers and feeder lengths.

Evidence that the impact of variable speed air conditioners may be different for Australian networks is given in [21] which contains an indication that penetration levels on French networks could be higher than those for North American networks before the 5% voltage THD limit is reached. The French electricity network is a 230 V network with residential customers supplied through delta-star transformers which closely resembles the Australian case. The study presented states that 30% penetration for one rectifier design and 10% for the other two rectifier designs would result in the 5% voltage THD limit being reached on French networks although the methodology and other details of this study are not provided. These figures are considerably higher than those seen for the North American network giving an indication that North American results may not be applicable to the Australian case.

The study presented in [22], examines a 240 V network. A model of a distribution system is constructed and the effect of first generation variable speed air conditioners on distribution system harmonic levels is examined. The study showed that relatively low penetration of air conditioners, (approximately 30%), resulted in very large localised voltage THD levels. It was also found that in order to maintain voltage THD levels below 5%, first generation variable speed air conditioner penetration
must be kept below 12%. Again, this study is limited since it examines the air conditioner load in isolation and does not provide for the combined effects of other non-linear loads.

The studies described in [4], [20] and [21] are now quite dated. There is evidence presented in [23] which indicates that air conditioner electrical design has evolved substantially since these studies were performed. Laboratory testing of the input current characteristics of a variable speed air conditioner showed harmonic current values considerably less than those reported in the aforementioned studies [23]. This Australian study concluded that harmonic currents produced by variable speed air conditioners were not anticipated to be of major concern. However, this conclusion is based only on the results of testing of one brand of air conditioner in isolation.

Air conditioner penetration now stands at approximately 50% for at least one state in Australia [15] and similar penetration levels are likely in other states. Even if only one half of these air conditioners were inverter driven this is a penetration level considerably higher than those seen in [4], [20], [21], and [22] which, according to those studies, would produce very high harmonic voltage levels. Consequently, it is clear that the studies do not take into account all of the important factors necessary to make accurate determinations of the impact of variable speed air conditioners on the electricity distribution network.

2.3.3 Compact Fluorescent Lamps (CFLs)

The CFL is a domestic non-linear load which will experience a very high growth in penetration levels over the next 2 – 3 years. CFL technology has been in existence since the late 1980s. It is only now, however, that penetration levels are increasing to a point where the CFL load cannot be considered negligible compared to other non-linear domestic loads. Development of the CFLs over the last 20 years has seen those with magnetic ballasts replaced exclusively with electronic ballasts. Electronic ballast technology has also developed to a point where there are now several ballast types available including some which aim to minimise the impact of the CFL on power quality. As there is significant literature on the characteristics of the CFLs with respect to harmonic distortion it is worth reviewing this before the potential
effects of widespread mass installation of CFLs on the electricity network is investigated.

2.3.3.1 Input Current Characteristics of the CFL

The electrical properties of the CFL are strongly dependant on the design of the ballast used to drive the lamp. Magnetic ballasts display characteristics similar to those of traditional fluorescent lamps and were employed to drive the first generation of CFLs. As stated, magnetic ballasts are now rare, having been replaced by electronic ballasts.

The basic electrical characteristics of fluorescent lighting loads, especially CFL lighting, is non-linear with high current-waveform distortion. For the CFL, this was identified almost as soon as CFL technology emerged and there are several studies [13], [24], [25], [26] and [27] from the late 1980s and early 1990s which investigate the harmonic characteristics of the CFL. At that time, electronic ballasts for CFLs was an emerging technology and many of these studies contain testing and analysis of both magnetically ballasted and electronically ballasted CFLs.

The majority of the studies are in reasonable agreement with regard to the harmonic behaviour of the CFL. [13], evaluates the harmonic distortion characteristics of energy saving lamps, including CFLs, which at that time were a new class of lamp. The study states that the CFL current waveform exhibits significant current distortion with pulse-like features, implying the existence of a multitude of odd order harmonics. The current THD of the tested CFLs was found to be 119.8%. Analysis of the testing methodology used in this study alludes to some measurement inaccuracy due to instrumentation which may impact on the results of the study. In [25] the current waveforms of the CFLs were also found to exhibit significant distortion. The current THD of the tested CFLs was found to range between 82.4% and 109%. The study detailed in [26] presents the results of laboratory testing of CFLs. Fourteen CFLs with magnetic ballasts and fourteen CFLs with electronic ballasts were tested. The current THD for CFLs with magnetic ballasts was found to range between 8% and 14%, while the current THD for CFLs with electronic ballasts was found to range between 116% and 142%. The study presented in [27] is an investigation of the
harmonics caused by CFLs. Five CFLs with magnetic ballasts and five CFLs with electronic ballasts were assessed. Results were comparable with those found in [26] with the current THD levels for CFLs with magnetic ballasts being in the range of 8.1% - 15.7% and the current THD levels for CFLs with electronic ballasts being in the range of 98% - 114%.

Although there is no reason to doubt the veracity of the studies reported in [13], [25], [26] and [27], they are now quite dated. At the time of these studies, CFLs, especially those with electronic ballasts were an emerging technology. It is reasonable to assume that advances and design evolution to CFL ballast technology occurred over the subsequent decade. Some of the studies include CFLs with magnetic ballasts which are now relatively unheard of.

Another example of ongoing CFL technology development can be found in [24] and [27] which refer to a new technology in ballasts which can limit harmonic distortion, although no reference is made to studies of these new devices. The studies in [13] and [25] do not specifically state the type of ballast used to drive the lamps studied. If these lamps are driven by magnetic ballasts, they are not relevant to the modern case.

Between the early and late 1990s, there is little literature concerning CFLs. This may be due to interest in CFLs diminishing during this time as they were still quite expensive and the technology was relatively mature. In recent years, energy efficiency has become an issue that has received considerable attention for various environmental, commercial and political reasons. Consequently, CFLs are now seen as an important energy saving initiative and [12], [28], [29] and [30] present studies of the electrical characteristics of the CFL undertaken after the year 2000.

Recent studies of CFL characterises find that the modern CFLs without power factor correction have current THD levels greater than 100%. Results in [28] show that the current THD of the CFL is typically 150% with some CFLs having current THD levels of up to 175%. [29], outlines laboratory testing of 11 CFLs. Similar findings to those presented in [28] were found. Current THD levels were determined to be above
100% with the highest being 174%. The study presented in [12] principally explores the implications of widespread CFL installation on the electricity distribution network; however, some results of laboratory testing of CFLs are presented. The test results indicate that the tested CFLs fall into three categories as follows:

1. Those that comply with the limits specified in Table 3 of Clause 7.2 Part B of AS/NZS61000.3.2 [9], the Australian and New Zealand standard which limits current harmonic emissions from equipment rated less than or equal to 16 A per phase
2. Those that comply with the alternative criteria in Clause 7.3 Part B of AS/NZS61000.3.2
3. Those that do not comply with AS/NZS61000.3.2

Studies of CFLs which include power factor correction indicate that this type of CFL is characterised by current THD levels significantly less than those of standard CFLs. The study presented in [30] is a comparison of the performance of a high power factor type CFL with a standard CFL without power factor correction. 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 was found to be approximately 17% compared to 124% for the standard CFL.

Although more recent studies presented in [12], [28], [29], and [30] have been conducted using modern instrumentation as well as modern CFLs, they are less than comprehensive in methodology or reporting of findings or both. Both [29] and [30] use uncalibrated and unregulated sources to conduct the experiments. This is less than ideal as any distortion on the input voltage waveform may affect the results of the tests. None of the studies investigate the full harmonic spectrum of the input current waveform, instead only reporting on current THD. Identification of the dominant harmonics of the current waveform is important since high order harmonics have behaviour, limits and potential effects which can be quite different to those of lower order harmonics.
Notwithstanding the limitations of all of the aforementioned, there are very few studies which have examined the input current characteristics of CFLs over the range of operating conditions likely to be encountered on the electricity distribution network in general, let alone the specific case of Australian networks. The Australian voltage standard AS60038:2000 [31] specifies a nominal LV voltage range of 230 V +10%/-6%. A further 5% voltage drop is allowed for in the installation wiring. Thus any equipment connected to Australian low voltage supplies is expected to operate over a voltage range of 230 V +10%/-11% or 253 – 205 V.

The study detailed in [32] investigates the effects of varying voltage levels on the performance of CFLs, in this case, specifically undervoltage. This study was performed in 1992 and consequently is quite dated. Both CFLs with magnetic and electronic ballasts are included in the testing. The study was based on a 120 V nominal system and involved applying voltages of 120 V, 110 V and 100 V to the CFLs to determine the effect of reduced voltage on CFL input current characteristics. For CFLs with magnetic ballasts, illuminance, active power and apparent power decreased as voltage was reduced. Current THD increased from 11% at 120 V to 17% at 100 V. For CFLs with electronic ballasts THD levels remained relatively constant as the voltage was reduced. A CFL with magnetic ballast and power factor correction was also tested. The study found that THD levels and current wave shape varied widely with voltage level. While this study gives an indication of the performance of CFLs due to undervoltage conditions and indicates that voltage level will have an impact on the behaviour of CFLs, it is limited by the fact that it does not explore the behaviour of the CFLs over the full voltage range. The use of the North American nominal voltage level of 120 V as opposed to the nominal voltage of 230 V on Australian electricity networks renders the relevance of the study to the Australian case questionable as the design for lamps to be used at 230 V may be different.

Data shown in [33] also indicates that voltage level has an impact on CFL performance. Current THD decreased as voltage decreased, contrary to the findings of [32] for CFLs with electronic ballasts. The results of this study are not well presented and it is difficult to determine the exact effects that voltage levels have had.
on CFL performance. The study presented in [34] also indicates that THD will increase with increasing supply voltage levels although little detail is given. The methodology used and the lamps tested in this study are poorly defined.

CFLs connected to the electricity distribution network are also likely to be exposed to some level of harmonic distortion on the voltage input waveform. Results in [30] indicate that this will affect the current harmonics drawn by the CFL, though this study does not explore the effects of voltage input waveform distortion on the electrical characteristics of the CFL. The study presented in [35], investigates the effect of supply harmonics on CFLs with both magnetic and electronic ballasts. It was found that magnetic ballasts were less affected by supply harmonics than electronic ballasts. Current THD was found to deteriorate as supply harmonic distortion increased. This study is now quite dated and is based on a 120 V nominal voltage level. The levels of harmonic distortion used for some of the tests were extremely high and not representative of levels likely to be measured on Australian electricity distribution networks.

2.3.3.2 Possible Harmonic Distortion Impacts of Widespread Mass Installation of CFLs on the Electricity Distribution Network

A single CFL presents only a very small load on the electricity distribution network and would not be of concern with respect to harmonic distortion. However, the potential connection of thousands or perhaps even millions of these devices to the electricity network gives rise to concerns about possible increases in harmonic distortion levels. Millions of CFLs connected together cannot be considered a negligible load. If harmonic distortion caused by these CFLs reaches unacceptable levels it will be very difficult to mitigate these harmonics due to the highly distributed nature of the CFL currents.

The potential for harmonic distortion problems on electricity distribution networks due to increased penetration of CFLs has been the subject of a significant number of studies. The majority expect that widespread adoption of CFLs will lead to an increase in harmonic distortion problems on electricity distribution networks. The
studies [12], [26], [36], [37], [38], [39], [40], [41] and [42] show that widespread adoption of CFLs will have an adverse effect on network harmonic voltage levels.

One of the conclusions of [36], is that the most significant power quality impacts to distribution systems come from low power factor electronic equipment of which CFLs are an example. According to this study, the low power factor (true power factor) is generally due to distortion as opposed to displacement and cannot be corrected by power factor correction capacitors. As a result, utilities are probably experiencing higher than realised transmission and distribution losses from the higher line currents required to service low true power factor devices. The study also states that power line carrier systems are easily interfered with by electronic ballasts. An example is given of a utility which had to correct a control system that was rendered inoperable due to interference from electronic ballasts. To ensure efficient and trouble-free operation of the electricity network, the study recommends that CFLs be designed such that current THD levels are kept below 34% and power factor is kept greater than or equal to 0.9.

A report prepared for the New Zealand Electricity Commission on the assessment of the benefits of installing CFLs, [40] (2007), agrees in principle with the findings of [36], stating that with increased CFL penetration power quality issues are expected to arise. The report states that higher harmonic content at higher harmonic orders caused by CFLs may have an effect on older technology audio frequency ripple control signals. The report details several case studies in which voltage THD levels will exceed limits with increased CFL penetration. Both [36] and [40] base their conclusions on the non-linear characteristics of the CFL itself. No simulations or field monitoring have been undertaken to verify these conclusions.

The studies presented in [26], [37], [38], [39] and [41] also present simulation and modelling scenarios which indicate that widespread adoption of CFLs will lead to a deterioration of harmonic distortion levels. In [26], the results of a computer simulation of three, real-life 13.8 kV feeders supplying customers with non-linear loads including CFLs indicate that for a 15 kV class feeder with a maximum 10 MVA load, the total load of electronically ballasted CFLs should not exceed 100 kW
if the voltage THD is to be kept less than or equal to 5%. It was found that 3000 homes using CFLs will create a total (CFLs plus other loads) non-linear load of 300 – 500 kVA. Such a non-linear load may be sufficient to cause unacceptable voltage distortion. The computer simulation is supported by laboratory testing and monitoring at residential homes. Three different feeder scenarios are modelled; an overhead feeder, a predominately overhead feeder with some underground and a predominately underground feeder with some overhead. The model was constructed to include other non-linear residential loads and reflects the presence of refrigerators, motors, resistive heating, computers and televisions along with the CFLs. The current THD of the CFLs used in the simulation is greater than 100%. Another important finding of the study is that the harmonics due to the CFLs tend to add with harmonics due to the televisions and PCs.

In [37], a statistical approach for modelling the harmonic currents drawn by CFLs was adopted. The models were developed based on measurements performed using a sample of about 50 CFLs with electronic ballasts. The test results indicate that there is little disparity between harmonic current phase angles for the different ballasts tested. This indicates that the harmonic currents from different types of CFLs will likely add together as opposed to cancel, particularly for the 3rd and 5th harmonics. The theoretical results were validated by field monitoring. The contribution of CFLs to voltage distortion in distribution systems was found to be substantial compared with the contribution of other common domestic appliances such as televisions and halogen lamps, particularly for the 5th harmonic. On an average network with a fault level of 120 MVA and loaded to 30% of nominal power, the 5th harmonic voltage would rise from 3.5% to 4.3% if each domestic customer installed 5 CFLs.

A study on the influence of CFLs on a weak network supplied by photovoltaics with a 30 kVA inverter is presented in [39]. The network studied is located on one of the Greek Islands. Much of the load on the island is comprised of televisions, irons, low power fridges and lighting. High power devices are not used due to the constraints of the power supply. The typical load profile is 50% lighting and 50% other load. A computer simulation of the network has been performed using PSCAD/EMTDC software to investigate the impact of replacing traditional lighting sources with
CFLs. Loads other than the CFLs have been modelled as linear and the CFLs themselves are modelled as odd order current harmonic sources for harmonic currents up to the 19th order. The background voltage harmonic level due to the inverter was set to 3.14%. It is reported that replacement of incandescent globes with CFLs increased the voltage THD levels at some buses from 3.14% to 4.5% without the effects of other non-linear loads even being considered.

The study detailed in [38], presents a simulation study carried out for a Melbourne distribution company which included modelling of existing non-linear loads (e.g. televisions, VCRs, PCs). The study showed that for a 22 kV feeder loaded to 80% of nominal capacity, increased penetration of CFLs raised voltage THD levels from 3.5% to 5%. This outcome indicates the potential of CFLs to raise harmonic voltage levels.

The theoretical study presented in [12] examines the implications for distribution networks for widespread adoption of CFLs in terms of losses and power quality. A model of a typical overhead and underground distribution network in New Zealand was constructed. The effect of different types of CFL, as determined by laboratory measurements, on these distribution network models was examined. The CFLs have been divided into three classes based on laboratory measurements with reference to the Australian and New Zealand standard for current harmonic emission, AS/NZS61000.3.2 [9]. These classes being good, average and poor. The distribution network is modelled from the low voltage domestic premises up to the 220 kV bulk supply point. The domestic load was modelled as a 3 kW linear load in addition to the lighting load. The number of CFLs installed at each residence is not clear. The main findings are that CFLs will increase harmonic losses in distribution systems and that poor quality CFLs will significantly increase the harmonic voltage distortion at higher voltage levels. It was also found that CFLs have the potential to cause malfunction of audio frequency ripple control signalling systems.

A technology assessment of incandescent lamp replacement with CFLs is given in [41]. The study states that a low penetration of CFLs will have little effect on power quality levels. However, the study finds that if penetration of low power factor CFLs
is increased to near 100%, the CFL must be considered as a significant non-linear load and may increase levels of voltage harmonic distortion above set limits. The findings in this study are based on modelling of a residential load. The peak consumption of the house modelled is 4.5 kW. Lighting comprises 20% of the load. Other appliances were modelled to draw square wave currents. For the model, all original globes are considered to be 60 W incandescent which are replaced with 12 W CFLs. Analysis of the model shows that replacing all lamps in the house with high power factor CFLs leads to a 1% increase in voltage THD levels. Replacement of globes with low power factor CFLs, the increase was found to be just below 3%. This may cause levels to exceed limits if significant voltage THD is already present on the network.

Almost all of the studies examined indicate that widespread installation of CFLs will likely have an adverse impact on distribution system harmonic voltage distortion levels. Those that do not, such as [28], assume very low penetration of CFLs. With a major, recent shift toward energy efficiency and the Australian Government banning incandescent globes, the CFL is the only currently available alternative to traditional inefficient incandescent globes. Thus CFL penetration can be expected to rise to levels nearly equal to that of incandescent globes within the next few years. Consequently, studies such as [37] and [38] which are based on low levels of CFL penetration may no longer be relevant.

For the studies that indicate that CFLs will have an adverse effect on power quality levels a number of them may no longer be relevant due to changes in load characteristics over time. The studies completed in the early 1990s which modelled residential loads would likely not be relevant today. None of these studies include air conditioners in their load models. Air conditioner penetration in Australia is now significantly higher than it was in the early 1990s. Other examples of the growth in residential non-linear loads include home theatre systems as well as personal computers. Many of the studies are also based on atypical networks or loading levels that do not adequately take into account the presence of other non-linear loads.
The analysis of the effects on power factor of the CFLs is also worthy of mention. Power factor is analysed in many studies without reference being made between ‘displacement’ and ‘true’. Lack of reference to the power factor type is a cause for confusion as these two issues are quite different in their nature, effects on the network and mitigation techniques.

In relation to recent studies, there are several points which deserve further investigation. Foremost is that many of the studies are performed using overseas distribution systems. The distribution systems in the United States are considerably different to those in Australia and although European distribution systems may be similar to the Australian distribution system, there are subtle differences that may render the models presented less relevant to the Australian case. Secondly, many studies assume that the remainder of the domestic load is linear. This will eliminate any of the effects that the other non-linear loads will have on the behaviour of the domestic load, including harmonic addition or cancellation and power factor implications. Consequently, it is difficult to determine whether the model presented represents a worst-case scenario, best-case scenario or something in between.

2.3.4 Motor Loads

Refrigeration motors for refrigerators and older style air conditioners are a saturable load, as are ceiling and pedestal fans. The components used in manufacturing domestic motor loads are driven by a need to keep costs as low as possible to maintain market share. Insufficient or poor quality steel is often used in domestic motors leading to saturation and non-sinusoidal currents. Motors exhibit distortion in current waveform when saturated in much the same way as transformers. In these cases, harmonics are generated due to the non-linear magnetising characteristics of the steel [43].

Only one study, [23] (2005), could be found that investigated the potential impact of motor loads on distribution system power quality. In this case, the motor load is a direct-on-line supplied air conditioner. The study has a major benefit in that it is an Australian study which bases findings on Australian conditions. The study finds that
harmonics due to motor saturation are not a major concern. However, this study only tested a single type of air conditioner.

### 2.3.5 Combinations of Non-Linear Loads

In practice, there will be a range of linear and non-linear loads operating simultaneously and interacting with each other. The harmonic currents of the non-linear loads may add or cancel depending on the relative phase angles of the harmonic currents. As there would be many different load mixes that may be operating this interaction may be quite complex. There appear to be few studies which examine the effects of combined non-linear domestic loads on electricity distribution system power quality levels. Instead, most studies focus on a specific type of load or appliance and its potential impact.

A study which examines the impact combined non-linear loads on North American distribution network harmonic levels is described in [44]. Three distribution feeders were computer modelled; an overhead network, a predominately overhead network with an underground component and a predominately underground network with an overhead component. Three classes of non-linear loads are considered in the study based on the electrical behaviour of different types of AC to DC rectifiers.

The main conclusions of the study are that for a 15 kV class feeder with a maximum of 10 MVA installed load, in order to maintain voltage THD levels below 5%, the non-linear component of the load should be kept below 300 kW if the characteristic current THD of the load is less than 90%. If the characteristic current THD of the load is above 100%, this figure falls to 100kW. The study also finds that the susceptibility of feeders to increases in harmonic currents due to non-linear loads differs greatly from one system to the next. It is also stated that values of shunt capacitance, linear load power and power factors as well as background harmonic levels are significant factors in determining the amount of non-linear load that is permissible before voltage THD limits are exceeded.

While the study clearly shows that high penetration of electronic loads can lead to increased harmonic levels, there are several factors that diminish its relevance to both
the modern situation and the Australian case. The study was published in 1995 which makes it over 15 years old. There has been significant evolution in terms of both magnitude and appliance mix of the domestic load in that time. Given this growth in load, the main conclusions of the study appear to be quite pessimistic. The figures for non-linear loading levels are quite small on a per customer basis, the 300 kW level allows for approximately 100 W of non-linear load per customer, a value which would be exceeded by modern domestic loads. In spite of this, major harmonic problems on distribution feeders are relatively rare. The study also uses North American networks. Thus the relevance of the study to the Australian case may be questionable.

Overall, one of the main limitations of the many studies is that they consider single phase loads and their harmonic levels without taking into account the interaction of single-phase and three-phase loads. Results in [45] clearly indicate that there will be harmonic cancellation of harmonic currents due to mixing of single-phase and three-phase. A mixture of single-phase and three-phase loads, as is the case in practice, results in reduced THD levels compared to the case where single-phase loads are examined in isolation.

2.4 Summary

It is clear that the modern domestic load has now evolved into one which is far from negligible with respect to potential power quality impacts on the electricity distribution systems. Understanding the impact of the modern domestic load on power quality is important so that:

- Electricity distribution utilities can make informed planning and design decisions can be made to accommodate it if necessary.
- Equipment standards can be influenced to ensure compatibility between equipment emission levels and distribution network requirements (planning levels).
- Manufacturers can design equipment with sufficient immunity to operate on the electricity distribution network (compatibility levels).
The key distribution system parameters that will determine harmonic levels are load
density, network impedance and type of loads connected. There are relatively few
studies which examine the potential impacts of modern domestic loads on
distribution system power quality. Many of those that do are dated, possibly limiting
their relevance to the modern case. All indications are that the characteristics of
domestic loads have changed considerably over the last decade due to the
proliferation of electronic equipment supplied through power electronic front ends.
Many of the older studies are based on predictions of appliance penetration levels,
such as inverter driven air conditioners, which have now been exceeded.

Those studies which are more up to date generally only examine the effects of a
specific type of load in isolation ignoring the contributing effects of other load types
both single-phase and three-phase. This produces an oversimplified view of the load
characteristics which may not reflect actual real world conditions. Studies clearly
indicate that diversity and attenuation are very important factors in predicting the
impact of distributed single phase power electronic loads on power quality.

The bulk of the studies are also performed on North American electricity distribution
systems. North American electricity distribution systems are considerably different
to the Australian distribution system. North America utilises a 110 V nominal low
voltage system. This leads to many more transformers and much shorter feeder
lengths. The only comparison between a European electricity distribution system,
which will be closer to the Australian case, and a North American electricity
distribution system indicated that results will be quite different between the two.

The development of the domestic load into a significant non-linear load, the lack of
comprehensive studies into the potential of the modern domestic load to create power
quality issues and the very likely increase of CFL penetration to very high levels
justifies the requirement for a thorough investigation into the potential power quality
impacts of the modern domestic load on the electricity distribution system. To ensure
relevance to the Australian case, such a study must utilise typical Australian network
construction data, loading levels and background power quality levels.
CHAPTER 3 : ELECTRICAL PERFORMANCE AND CHARACTERISTICS OF THE MODERN COMPACT FLUORESCENT LAMP

3.1 Introduction

The decision by the Australian Federal Government to ban the sale of traditional inefficient incandescent light globes by 2010 [3] will have implications on the characteristics of the domestic lighting load. This decision has been made in an effort to reduce electricity demand both to ease supply constraints and as an attempt to reduce greenhouse gas emissions arising from electricity generation. Although LED lighting technology is maturing, the only viable alternative to the traditional incandescent globe at present is the CFL. As a consequence, CFL penetration levels have risen from very low levels to account for almost the entire lighting load in just a few years. Given this large increase in CFL penetration levels, although this thesis investigates the potential impact of all modern domestic appliances on distribution network power quality, a special emphasis is placed on the CFL.

According to [5], the domestic lighting load accounts for 9% of domestic electricity usage. CFLs, which were first developed in the 1980s, present a significant energy efficiency advantage over the traditional incandescent globe. Modern CFLs often require only 25% of the active power required by a traditional incandescent light globe for the same light output. However, the CFL is also a well-known non-linear load. These non-linear characteristics present other technical implications for the electricity distribution network, particularly in the areas of harmonic emission and power factor.

This chapter addresses the shortage of concise information with regard to the electrical performance and characteristics of the modern domestic CFL. This is achieved by a laboratory testing regime designed to identify the electrical performance and characteristics of the modern CFL over a range of influence factors likely to be seen on Australian distribution networks. These influence factors include various levels of input voltage magnitude as well as varying levels of input voltage harmonic distortion. A range of CFL brands and design types (e.g. straight, spiral) have been taken into consideration in this testing regime. Thorough understanding of
the modern CFL is critical since lighting load forms a significant portion of domestic load. The results obtained from the testing will be used in the development of the domestic load models to be utilised in subsequent chapters of this thesis.

3.2 Test Methodology

3.2.1 CFLs Assessed

The electrical performance of a total of 25 different CFLs has been measured and assessed. Table 3.1 is a list of the CFL globes which have been tested. These CFLs represent a range of brands, construction types and ratings from a cross section of suppliers and at a variety of 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 harmonic current components.
### Table 3.1: Details of CFLs Tested

<table>
<thead>
<tr>
<th>Reference no.</th>
<th>Brand</th>
<th>Sub-brand</th>
<th>Construction (Spiral/Straight)</th>
<th>Rating (W)</th>
<th>Equivalent Rating (W)</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Mirabella</td>
<td>Mini Spiral</td>
<td>Spiral</td>
<td>15</td>
<td>75</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>Mirabella</td>
<td>Mini Spiral</td>
<td>Spiral</td>
<td>8</td>
<td>40</td>
<td>4.00</td>
</tr>
<tr>
<td>C</td>
<td>Mirabella</td>
<td>Slimline</td>
<td>Straight</td>
<td>15</td>
<td>75</td>
<td>5.00</td>
</tr>
<tr>
<td>D</td>
<td>Osram</td>
<td>Duluxstar</td>
<td>Straight</td>
<td>14</td>
<td>75</td>
<td>4.66</td>
</tr>
<tr>
<td>E</td>
<td>Fairway</td>
<td></td>
<td>Straight</td>
<td>11</td>
<td>60</td>
<td>2.50</td>
</tr>
<tr>
<td>F</td>
<td>Fairway</td>
<td></td>
<td>Straight</td>
<td>20</td>
<td>100</td>
<td>3.75</td>
</tr>
<tr>
<td>G</td>
<td>Philips</td>
<td>Genie</td>
<td>Straight</td>
<td>11</td>
<td>60</td>
<td>4.10</td>
</tr>
<tr>
<td>H</td>
<td>Nelson</td>
<td></td>
<td>Spiral</td>
<td>15</td>
<td>75</td>
<td>3.10</td>
</tr>
<tr>
<td>I</td>
<td>Coles</td>
<td></td>
<td>Straight</td>
<td>15</td>
<td>75</td>
<td>4.50</td>
</tr>
<tr>
<td>J</td>
<td>Mayfair</td>
<td></td>
<td>Straight</td>
<td>15</td>
<td>75</td>
<td>2.50</td>
</tr>
<tr>
<td>K</td>
<td>Mayfair</td>
<td></td>
<td>Straight</td>
<td>11</td>
<td>55</td>
<td>2.50</td>
</tr>
<tr>
<td>L</td>
<td>Facets</td>
<td></td>
<td>Spiral</td>
<td>20</td>
<td>100</td>
<td>4.00</td>
</tr>
<tr>
<td>M</td>
<td>Facets</td>
<td></td>
<td>Straight</td>
<td>15</td>
<td>75</td>
<td>3.00</td>
</tr>
<tr>
<td>N</td>
<td>SAS</td>
<td></td>
<td>Straight</td>
<td>11</td>
<td>55</td>
<td>3.99</td>
</tr>
<tr>
<td>O</td>
<td>Intracell</td>
<td></td>
<td>Straight</td>
<td>15</td>
<td>75</td>
<td>3.99</td>
</tr>
<tr>
<td>P</td>
<td>Eco Bulb</td>
<td></td>
<td>Spiral</td>
<td>15</td>
<td>75</td>
<td>~7.00</td>
</tr>
<tr>
<td>Q</td>
<td>Osram</td>
<td>Duluxstar</td>
<td>Straight</td>
<td>11</td>
<td>60</td>
<td>4.66</td>
</tr>
<tr>
<td>R</td>
<td>Ozone</td>
<td>Classic</td>
<td>Spiral</td>
<td>15</td>
<td>75</td>
<td>4.95</td>
</tr>
<tr>
<td>S</td>
<td>Crompton</td>
<td>Lightstar</td>
<td>Spherical</td>
<td>20</td>
<td>100</td>
<td>19.90</td>
</tr>
<tr>
<td>T</td>
<td>Switch On Globe</td>
<td></td>
<td>Straight</td>
<td>11</td>
<td>55</td>
<td>2.99</td>
</tr>
<tr>
<td>U</td>
<td>Switch On Globe</td>
<td>X-Lite</td>
<td>Spiral</td>
<td>11</td>
<td>55</td>
<td>2.99</td>
</tr>
<tr>
<td>V</td>
<td>Philips</td>
<td>Genie</td>
<td>Straight</td>
<td>14</td>
<td>75</td>
<td>4.10</td>
</tr>
<tr>
<td>W</td>
<td>Philips</td>
<td>Genie</td>
<td>Straight</td>
<td>18</td>
<td>100</td>
<td>4.10</td>
</tr>
<tr>
<td>X</td>
<td>Mirabella</td>
<td>Slimline</td>
<td>Straight</td>
<td>18</td>
<td>100</td>
<td>3.99</td>
</tr>
<tr>
<td>Y</td>
<td>Mirabella</td>
<td>Slimline</td>
<td>Straight</td>
<td>10</td>
<td>60</td>
<td>3.99</td>
</tr>
</tbody>
</table>

#### 3.2.2 Test Schedules

Each lamp was subjected to a number of tests to determine electrical performance under a range of input voltage conditions, referred to as influence factors, likely to be experienced on Australian electricity distribution networks. Each lamp was subjected to five distinct tests. Each of these tests involved applying different input voltage magnitudes and input voltage waveform distortion levels. The first three tests were designed to examine the operation of the CFLs at voltage levels representing the
range of operating conditions that may be encountered on a distribution network under normal operating conditions. Two test waveforms which were designed to provide an indication of the behaviour of the CFLs at differing levels of input voltage waveform harmonic distortion. Each of the harmonically distorted test waveforms applied to the lamps utilised a 230 V fundamental voltage component. Table 3.2 shows the full schedule of tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Middle of Range Voltage</td>
<td>Continuous 230 V</td>
</tr>
<tr>
<td>2</td>
<td>Low Voltage</td>
<td>Continuous 207 V</td>
</tr>
<tr>
<td>3</td>
<td>High Voltage</td>
<td>Continuous 253 V</td>
</tr>
<tr>
<td>4</td>
<td>Harmonic Test Waveform 1</td>
<td>Continuous Harmonic Test Waveform 1</td>
</tr>
<tr>
<td>5</td>
<td>Harmonic Test Waveform 2</td>
<td>Continuous Harmonic Test Waveform 2</td>
</tr>
</tbody>
</table>

Table 3.3 details the specific magnitudes used for each of the harmonic waveforms shown in Table 3.2. These harmonic levels were determined based on the data collected for the Australian Long Term Power Quality Survey (LTNPQS) project [8] as well as a number of other field measurements. These measurements indicated that 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 contributions are low order odd harmonics such as 3rd and 7th. Higher order harmonics have been noted to be generally small. Further, it is well known that most low voltage supply voltage waveforms exhibit a flat top characteristic due to 3rd harmonic currents associated with switch mode power supplies. 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 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 conducted for this thesis confirms these observations. Field monitoring also demonstrated a 7th harmonic phase angle close to 50 degrees. Harmonic test waveforms 1 and 2 have THD levels of 3.3% and 4.7% respectively.
Figures 3.1 and 3.2 show the voltage waveforms for Harmonic Test Waveforms 1 and 2 respectively.

<table>
<thead>
<tr>
<th>Harmonic Test Waveforms</th>
<th>Harmonic Test Waveform 1</th>
<th>Harmonic Test Waveform 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic Order</td>
<td>Harmonic</td>
<td>Phase</td>
</tr>
<tr>
<td></td>
<td>Magnitude (% of Fundamental)</td>
<td>Angle (degrees)</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>180</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 3.1: Harmonic Test Waveform 1
In addition to schedule of tests described in Table 3.2, each lamp was tested for compliance with AS/NZS61000.3.2 [9]. This is the standard which specifies limits for harmonic current emissions for equipment with input current less than or equal to 16 A per phase. For the tests to determine compliance with AS/NZS61000.3.2 each CFL was assessed at the rated voltage as specified on the lamp packaging or on the lamp itself. Lamps which had a range of voltages specified (e.g. 220 – 240 V) were tested at 230 V.

3.2.3 Test Equipment

Each test level was applied to the globes using a California Instruments MX30-3PI programmable source. This device has a very low output voltage distortion level (~0.24% THD) when programmed to produce undistorted sinusoidal waveforms. It can also be used to apply various voltage and waveform distortion levels in order to test the response of equipment to a range of influence factors.

The instrument used for measurement of all tests parameters was the Hioki 3196 Power Quality Analyser. This device is a modern IEC61000-4-30 [46] Class A compliant power quality monitor. Current measurements were carried out using Hioki 9694 current clamps (0 – 5 A) connected to the Hioki 3196.

Figure 3.3 is a photograph of the test setup.
Figure 3.3: Photograph of Test Setup for Domestic CFLs

Figure 3.4 is a photograph of the measuring instrument, the Hioki 3196 Power Quality Analyser and Figure 3.5 is a photograph of the Hioki 9694 current clamp.
3.2.4 Lamp Aging

All of the lamps used in the testing regime were new at the commencement of testing. Each lamp was aged for a minimum of one hour before testing commenced. Lamp ageing was achieved by supplying all lamps with an undistorted voltage level of 230 V.

3.2.5 Test Procedure and Application of Tests Levels

The CFLs were mounted base down in a test board as shown in Figure 3.3. All tests were performed in an air conditioned laboratory where the temperature was regulated to be approximately 23 – 27 °C at all times.

The testing procedure for all tests, with the exception of testing for compliance with AS/NZS61000.3.2, which has specific detailed requirements, was as follows:

- At the commencement of each testing period, the globes were first stabilised at 230 V for 10 minutes before any test voltage levels were applied.
- Once the lamps were stabilised, the tests levels were applied for a further 5 minutes to allow the lamp to stabilise at the test voltage level
- Measurements were then taken of the parameters of interest using the power quality monitor over a 10 minute period. The measuring instrument was configured to log voltage (fundamental and harmonics to the 50th order plus THD), current (fundamental and harmonics to the 50th order plus THD) and power parameters (real, active (P) and non-active (Q) power and displacement power factor) at one minute intervals.

Assessment of lamps for compliance with AS/NZS61000.3.2 requires a specific testing procedure, some of which was not able to be met due to time or instrumentation constraints. As such a modified AS/NZS61000.3.2 assessment procedure was developed. This procedure, including the limitations encountered, was as follows:
• **Step 1** - According to strict application of AS/NZS61000.3.2 before any assessment lamps should be aged for at least 100 hours at rated voltage. This step was not feasible due to time constraints. Instead, the lamps tested were aged for at least one hour at a rated voltage level before assessment. It is unclear what effect a lack of aging will have on the assessment results, although no significant differences in lamp operation were observed over time. As the tests detailed in the thesis are comparative and all of the lamps tested were aged to a similar level before testing the lack of aging should not have a major impact on results.

• **Step 2** – According to AS/NZS61000.3.2 after aging, each lamp should be stabilised for 15 minutes at rated voltage before assessment. This was completed in the modified assessment procedure.

• **Step 3** - After stabilisation, measurements are performed. AS/NZS61000.3.2 calls for measurement of smoothed RMS harmonic currents and active input power over a 1.5 second window. 1.5 seconds is an unusual interval and was not a measurement option on any of the monitoring equipment available. Instead, measurements were made at one second intervals. The effect of this discrepancy is likely to be very small as tests showed that the lamp behaviour is quite stable over time.

• **Step 4** - AS/NZS61000.3.2 also defines the period over which 1.5 second measurements should be made. As CFLs are a quasi-stationary load, the measurement period is defined to be as long as required for results to be repeatable as defined in clause 6.2.3.1 of the standard. For the purposes of these tests, a period of one minute for each lamp was deemed sufficient to meet the requirements of the Standard.

• **Step 5** – According to the Standard compliance is assessed using the arithmetic average of the 1.5 second values for each parameter of interest and compared with the relevant limits. This step was completed using data measured at 1 second intervals as described above.
3.2.6 Analysis of Test Data

3.2.6.1 Analysis for Steady State Tests (Tests 1 – 5)

Each steady state test resulted in 10 minutes worth of data at one minute intervals, i.e. 10 readings. This data was reduced as follows:

- The first reading was discarded as it corresponds to a transient period where the instrument is beginning measurement and may not be reliable.
- The next five readings were retained.
- All other readings were discarded as it was observed that operation after a period of five readings was consistent and no further information would be obtained from the remaining readings.

This resulted in five readings for each test. These five readings were then arithmetically averaged and the result used as the characteristic level for further analysis.

3.2.6.2 Calculation of True Power Factor

As the measuring instrument did not possess the capability to measure true power factor (TPF) and displacement power factor (DPF) simultaneously, TPF needed to be calculated. In all cases where TPF is reported it has been calculated according to equation (3.1) where \( P \) is the active power and \( S \) is the apparent power.

\[
TPF = \frac{P}{S}
\]  

(3.1)

3.2.6.3 Reactive Power

Under non-sinusoidal conditions fundamental reactive power (Q) is defined as:

\[
Q = V_1 I_1 \sin \theta
\]  

(3.2)
where $\theta$ is the displacement power factor angle, $V_1$ is the fundamental voltage and $I_1$ is the fundamental current.

However, the measuring instrument calculates the quantity $Q_1$ using the apparent power ($S$) and the active power ($P$) as shown in equation (3.3).

$$Q_1 = \sqrt{S^2 - P^2}$$  \hspace{1cm} (3.3)

Under distorted conditions, which is the case in this thesis, this method of calculation will include not just the fundamental component of reactive power but all other power which is non-active and contributes to the value of apparent power ($S$), i.e. harmonic power. Thus it is somewhat misleading to label the quantity $Q$ as reactive power due to the fact that, as measured by the measuring instrument, the quantity $Q$ actually includes all non-active power including harmonic power. For this reason, the quantity $Q$ has been referred to as non-useful or non-active power throughout this chapter.

### 3.2.6.4 Analysis for AS/NZS61000.3.2 Compliance Test

The data analysis procedure for the AS/NZS61000.3.2 compliance test is outlined in the standard. As discussed in Section 3.2.5 various constraints made testing to the exact specification of the standard impossible. As such, the testing to AS/NZS61000.3.2 reported in this section is not fully compliant with the requirements of the standard. Consequently, the results of testing presented in this section are for information only.

### 3.3 Results of Lamp Testing

#### 3.3.1 230 V RMS Input Voltage

##### 3.3.1.1 Current Waveforms

Figure 3.6 illustrates the input current waveforms for each of the lamps tested when supplied with an undistorted 230 V RMS input voltage waveform. The input voltage
is also shown for comparison. It also shows that the majority of lamps draw current waveforms which are highly distorted. It can also be seen that there is quite a variation in the shape of the current waveform drawn by the different brands of lamp. The current waveform for lamp P, which has been designed to correct power factor by minimising waveform distortion is particularly distinct. This distinctive waveform is further emphasised in Figure 3.7 which shows a sample (best, worst and a case in between) of the different current waveforms observed across all of the lamps tested.

Figure 3.6: CFL Input Current Waveforms when Lamps were Supplied by an Undistorted 230 V RMS Input Voltage
3.3.1.2 Power Magnitudes

Figure 3.8 shows the active power (P) measured for each lamp when supplied with an undistorted 230 V RMS input voltage, expressed as a percentage of the lamp nominal rating. The figure shows that the vast majority of lamps draw less than their rated active power, in some cases much less with the most extreme being 48% less which is the case for lamp O.
Figure 3.8: Measured Active Power (P) Expressed as a Percentage of Rated Active Power when Lamps were supplied by an Undistorted 230 V RMS Input Voltage

Figure 3.9 shows the measured apparent power (S) for each lamp when supplied with an undistorted 230 V RMS input voltage, normalised by the lamp nominal active power rating. The figure shows that the apparent power drawn by each lamp, with the exception of lamps O and P, is considerably higher than the rated active power and higher than the active power drawn by each lamp. A comparison of active power levels with apparent power levels is shown in Figure 3.10. The difference between active and apparent power levels indicates that the lamps draw considerable non-active power due to poor power factor, either displacement or true. As the voltage level is fixed, the results for apparent power indicate that the RMS current drawn by most lamps will be considerably greater than the fundamental or rated current for most lamps.
Measured displacement and true power factor levels when the lamps were supplied by an undistorted 230 V RMS input voltage are shown in Figures 3.11 and 3.12 respectively. Examination of the data in these figures indicates the following:
1. The displacement power factor of the lamps is relatively high, averaging 0.89. The maximum is 0.97 for lamp P, while the minimum is 0.81 for lamp D. Displacement power factor was found to be leading in all cases. This suggests that the CFLs may provide some power factor correction to the traditionally inductive, or lagging power factor residential load.

2. The true power factor for all lamps, with the exception of lamp P, was found to be poor, averaging, 0.58 with lamp P included and 0.56 without. The high true power factor of lamp P, at 0.92, indicates that the power factor correction provided by this lamp refers to true power factor. It also demonstrates the effectiveness of the power factor correction technology included with this lamp.

3. The disparity between displacement and true power factor is an indicator of high harmonic and other non-fundamental components of current.

![CFL Displacement Power Factor (DPF) when Lamps were supplied by an Undistorted 230 V RMS Input Voltage](image)

Figure 3.11: Measured Displacement Power Factor (DPF) when Lamps were Supplied by an Undistorted 230 V RMS Input Voltage
3.3.1.3 Harmonic Components

Analysis of measured power and power factor values for the lamps tested indicated that the current drawn by the lamps would be rich in harmonic and other non-fundamental components. Figure 3.13, which illustrates the measured current THD levels for each lamp when supplied by an undistorted 230 V RMS input voltage, shows that all lamps, except lamp P, have current THD levels close to or exceeding 100%. The maximum current THD level is 171% which is the case for lamp Y.
Figure 3.14 shows the harmonic spectrum for the current drawn by each lamp expressed as a percentage of the fundamental current when the lamps were supplied by an undistorted 230 V RMS input voltage. The figure illustrates the level of harmonic current content in the CFL input current. It shows that the majority of lamps (with the exception of lamp P) draw significant levels of harmonic current (i.e. greater than 10%) for all odd harmonic orders up to the mid-thirties. This is significant since many non-linear devices connected to the electricity distribution network have low order (for example 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}) characteristic current harmonics with insignificant harmonic current components at orders above 20. CFLs therefore presents a load which were quite distinct from other common non-linear devices, for example, televisions and personal computers. This is of interest since the limits for higher order voltage harmonics as stipulated in the Australian Standard, AS61000.3.6 [47], are significantly less than those for lower order harmonics. The considerable levels of higher order harmonic currents drawn by CFLs may have the potential to increase high order voltage harmonic levels, possibly leading to excessive high order voltage harmonic levels.

Also of particular interest are the levels of harmonic currents at frequencies associated with audio frequency ripple control signals used for tariff and other
control purposes. Frequencies commonly used for these systems are close to the 15th and 21st harmonic. [12] presents evidence that the harmonic currents produced by CFLs could interfere with these systems. Figure 3.17 shows that there are significant current harmonic levels at these frequencies, approximately 20% for the 15th harmonic and 10% for the 21st harmonic for most CFLs.
Figure 3.14: CFL Input Current Harmonic Spectra when Lamps were Supplied by an Undistorted 230 V RMS Input Voltage
3.3.1.4 AS/NZS61000.3.2 Compliance Testing

Each lamp was tested for compliance with the limits for harmonic current specified in AS/NZS61000.3.2 using the method outlined in Section 3.2.5 of this thesis. Each lamp was tested at rated voltage. For those lamps with a recommended voltage range such as 220 V – 240 V tests were conducted at 230 V.

AS/NZS61000.3.2 [9] has two alternative clauses that a CFL may fulfil in order to be deemed be compliant with the Standard. Both criteria are detailed in Clause 7.3 Part (b) of the Standard. The first clause is based on strict power-related limits as reproduced in Table 3.4. This first clause is considerably more stringent than the second clause.

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Maximum permissible harmonic current per watt mA/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>0.35</td>
</tr>
<tr>
<td>13 ≤ n ≤ 39</td>
<td>(\frac{3.85}{n})</td>
</tr>
<tr>
<td>(odd harmonics only)</td>
<td></td>
</tr>
</tbody>
</table>

The second alternative clause for compliance is as follows [9]:

“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°. If the discharge lighting equipment has a built-in dimming device, measurement is made only in the full load condition.”

This criterion is considerably easier to meet than the first criterion and will allow devices drawing highly distorted waveforms to comply with the standard.

Of the 25 CFLs tested, only lamp P complied with the first criterion of the Standard based on strict power-related harmonic limits. When tested against the second less stringent criterion, 18 (72%) of the CFLs complied. This left seven (28%) lamps which failed to comply with the Standard outright. Table 3.5 shows a summary of the compliance performance of each CFL with respect to the limits specified in AS/NZS61000.3.2.
### Table 3.5: Performance of CFLs with respect to AS/NZS61000.3.2 Limits

<table>
<thead>
<tr>
<th>Lamp</th>
<th>Criterion 1</th>
<th>Criterion 2</th>
<th>Overall Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>B</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>C</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>D</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>E</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>F</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>G</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>H</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>I</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>J</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>K</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>L</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>M</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>N</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>O</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>P</td>
<td>Pass</td>
<td>Pass (limits only)</td>
<td>Pass</td>
</tr>
<tr>
<td>Q</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>R</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>S</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>T</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>U</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>V</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>W</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>X</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>Y</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
</tbody>
</table>

Analysis of the compliance performance of the lamps with respect to AS/NZS61000.3.2 identified a peculiarity in the criteria for compliance in the Standard. Lamp P which complies with the most stringent criteria of the Standard at rated voltage, (240 V in this case) and has what appears to be the most desirable input current waveform did not comply with the Standard based on the waveshape criteria when tested at 230 V. This appears to indicate that the waveshape clause in the Standard (second part of Clause 7.3 part (b)) is not achieving the best possible...
outcome in terms of input current waveform. The testing also indicates that the harmonic performance has some degree of dependence on input voltage magnitude.

3.3.2 Impact of Other Influence Factors on CFL Performance

In this section, the effect of various other electrical influence factors on CFL performance is examined. The influence factors tested are voltages at the upper and lower ends of the nominal low voltage range as well as harmonic distortion of the input voltage. The analysis of the impact of various influence factors on CFL performance presented in this section will form the basis for the development of the CFL load model outlined in the next chapter of this thesis.
3.3.2.1 Impact of Varying Undistorted Input Voltage Levels (Tests 2 and 3)

Tests 2 and 3 were designed to assess the impact of increasing or decreasing the sinusoidal supply voltage magnitude on the performance of the CFLs under test. Throughout this section the results obtained when the voltage was either increased or decreased has been expressed as a percentage of the value which was obtained when the CFL was supplied by an undistorted 230 V RMS input voltage. Table 3.6 shows the minimum, average and maximum values, expressed as a percentage of the 230 V value for RMS current, displacement power factor (DPF), fundamental current and total harmonic current when the lamps were supplied by an undistorted 253 V RMS input voltage. Use of minimum and maximum statistics is necessary due to the fact that some lamps may increase on 230 V levels for each parameter while others may decrease. Use of the two statistics shows the spread of performance. Table 3.7 shows the same information when the lamps were supplied by an undistorted a 207 V RMS input voltage.

Table 3.6: Basic Lamp Input Parameters when lamps were Supplied by an Undistorted 253 V RMS input Voltage (expressed as a Percentage of 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>I RMS</th>
<th>DPF</th>
<th>I Fund</th>
<th>Total Harmonic Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (%) of 230 V Value</td>
<td>96</td>
<td>98</td>
<td>98</td>
<td>95</td>
</tr>
<tr>
<td>Average (%) of 230 V Value</td>
<td>98</td>
<td>99</td>
<td>100</td>
<td>98</td>
</tr>
<tr>
<td>Maximum (%) of 230 V Value</td>
<td>106</td>
<td>100</td>
<td>103</td>
<td>140</td>
</tr>
</tbody>
</table>
Table 3.7: Basic Lamp Input Parameters when lamps were Supplied by an Undistorted 207 V RMS input Voltage (expressed as a Percentage of 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>I RMS (% of 230 V Value)</th>
<th>DPF (% of 230 V Value)</th>
<th>I Fund (% of 230 V Value)</th>
<th>Total Harmonic Current (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>96</td>
<td>100</td>
<td>95</td>
<td>52</td>
</tr>
<tr>
<td>Average</td>
<td>102</td>
<td>101</td>
<td>100</td>
<td>102</td>
</tr>
<tr>
<td>Maximum</td>
<td>106</td>
<td>101</td>
<td>104</td>
<td>107</td>
</tr>
</tbody>
</table>

Comparison of Tables 3.6 and 3.7 indicate that there is little variation in RMS current, DPF or fundamental current of the CFLs when the input voltage magnitude is varied. On average, values are within 2% of the 230 V values for all of the aforementioned parameters. The most extreme variation, as shown by the minimum and maximum statistics, indicates all values to be within ±6% of the 230 V value.

Figures 3.15(a) and 3.15(b) show RMS current levels for each CFL when supplied at 253 V and 207 V respectively. Figures 3.16(a) and 3.16(b) show the same information for DPF while Figures 3.17(a) and 3.17(b) show the same information for fundamental current.
While Tables 3.6 and 3.7 showed little variation in RMS current (I \text{ RMS}), displacement power factor (DPF) and fundamental current (I \text{ Fund}), the tables show that there is considerable variation in total harmonic. This is particularly the case when the lamps are supplied at 253 V RMS. However, analysis of Figures 3.18(a) and 3.18(b) which show the total harmonic current drawn by each lamp for 253 V RMS and 207 V RMS input voltage magnitudes indicates that lamp P is singularly responsible for this large variation. This lamp displays performance which is extremely atypical of all of the other lamps. If lamp P is excluded the other lamps all have total harmonic current values within 5\% of the 230 V value.
While the data presented in Tables 3.6 and 3.7 indicated the impact of varying the input voltage magnitude on basic parameters such as $I_{RMS}$ and DPF, it is also worth exploring the impact of changes in input voltage on the harmonic currents drawn by the lamps for individual harmonic orders of interest. The harmonic orders examined here are limited to those that are correlated with the dominant voltage harmonic orders on low voltage networks or those of special interest such as ripple control signal injection frequencies. Using this scenario, results are examined for $3^{rd}$, $5^{th}$, $7^{th}$, $15^{th}$ and $21^{st}$ harmonic orders. These harmonic orders will be those that are ultimately examined in the network models described later in this thesis.

Tables 3.8 and 3.9 show the minimum, average and maximum values, expressed as a percentage of the 230 V value, for $3^{rd}$, $5^{th}$, $7^{th}$, $15^{th}$ and $21^{st}$ harmonic currents when the lamps were supplied at 253 V RMS and 207 V RMS respectively.
Table 3.8: Individual Harmonic Current Behaviour when the lamps were Supplied by an Undistorted 253 V RMS Input Voltage (expressed as a Percentage of 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>3rd Harmonic</th>
<th>5th Harmonic</th>
<th>7th Harmonic</th>
<th>15th Harmonic</th>
<th>21st Harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (% of 230 V Value)</td>
<td>96</td>
<td>92</td>
<td>90</td>
<td>90</td>
<td>93</td>
</tr>
<tr>
<td>Average (% of 230 V Value)</td>
<td>101</td>
<td>95</td>
<td>95</td>
<td>96</td>
<td>106</td>
</tr>
<tr>
<td>Maximum (% of 230 V Value)</td>
<td>162</td>
<td>122</td>
<td>160</td>
<td>115</td>
<td>328</td>
</tr>
</tbody>
</table>

Table 3.9: Individual Harmonic Current Behaviour when the lamps were Supplied by an Undistorted 207 V RMS input Voltage (expressed as a Percentage of 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>3rd Harmonic</th>
<th>5th Harmonic</th>
<th>7th Harmonic</th>
<th>15th Harmonic</th>
<th>21st Harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (% of 230 V Value)</td>
<td>12</td>
<td>63</td>
<td>29</td>
<td>44</td>
<td>77</td>
</tr>
<tr>
<td>Average (% of 230 V Value)</td>
<td>99</td>
<td>105</td>
<td>109</td>
<td>101</td>
<td>104</td>
</tr>
<tr>
<td>Maximum (% of 230 V Value)</td>
<td>106</td>
<td>110</td>
<td>114</td>
<td>108</td>
<td>113</td>
</tr>
</tbody>
</table>

Tables 3.8 and 3.9 show that there is more variation for individual harmonic orders than was observed for basic parameters such as RMS current and DPF. Close analysis of the data in the tables reveals that average values are generally within 5% of 230 V values, however, outlying values indicated by minimum and maximum statistics show large variation. Figures 3.19 – 3.23 show the variation in harmonic current for each harmonic order shown in Tables 3.7 and 3.8. In each figure, the results for 253 V RMS input voltage are shown as part (a) and results for 207 V RMS input voltage are shown as part (b).
Figure 3.19(a): Variation of 3\textsuperscript{rd} Harmonic Current when Lamps were Supplied by an Undistorted 253 V RMS Input Voltage

Figure 3.19(b): Variation of 3\textsuperscript{rd} Harmonic Current when Lamps were Supplied by an Undistorted 207 V RMS Input Voltage

Figure 3.20(a): Variation of 5\textsuperscript{th} Harmonic Current when Lamps were Supplied by an Undistorted 253 V RMS Input Voltage

Figure 3.20(b): Variation of 5\textsuperscript{th} Harmonic Current when Lamps were supplied by an Undistorted 207 V RMS Input Voltage

Figure 3.21(a): Variation of 7\textsuperscript{th} Harmonic Current when Lamps were Supplied by an Undistorted 253 V RMS Input Voltage

Figure 3.21(b): Variation of 7\textsuperscript{th} Harmonic Current when Lamps were Supplied by an Undistorted 207 V RMS Input Voltage
Examination of Figures 3.19 – 3.23 shows that in almost all cases, harmonic currents decrease as input voltage magnitude is increased and vice-versa. The strong exception to this is Lamp P which shows behaviour atypical of all other lamps and exists as an outlier for all tests. These results reinforce those seen for total harmonic current for this lamp and demonstrate the extreme sensitivity to input voltage magnitude that the harmonic current performance of this lamp has. The observation that all of the lamps other than lamp P, which has special components not included in the other lamps, show little variation in most parameters as input voltage magnitude is varied over the nominal range indicates that the effects of input voltage magnitude can safely be ignored when the CFL is modelled.
3.3.2.2 Impact of Distorted Input Voltages (Tests 4 and 5)

Tests 4 and 5 were designed to evaluate the impact of distorted input voltage on the electrical behaviour of the CFLs. As detailed in Section 3.2.3, the distorted input voltage waveforms used for testing have been developed based on field measurements. For each of the test waveforms, the fundamental voltage is 230 V.

Table 3.10 shows the minimum, average and maximum values, expressed as a percentage of the undistorted 230 V value for RMS current, DPF, fundamental current and total harmonic current when the lamps were supplied with harmonic test waveform 1. Table 3.11 shows the same information when the lamps were supplied using harmonic test waveform 2.

**Table 3.10: Key Parameter Behaviour when lamps were Supplied using Harmonic Test Waveform 1**

(expressed as a Percentage of Undistorted 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>I RMS</th>
<th>DPF</th>
<th>I Fund</th>
<th>Total Harmonic Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum</strong> (% of Undistorted 230 V Value)</td>
<td>95</td>
<td>97</td>
<td>92</td>
<td>97</td>
</tr>
<tr>
<td><strong>Average</strong> (% of Undistorted 230 V Value)</td>
<td>102</td>
<td>98</td>
<td>99</td>
<td>102</td>
</tr>
<tr>
<td><strong>Maximum</strong> (% of Undistorted 230 V Value)</td>
<td>107</td>
<td>101</td>
<td>105</td>
<td>108</td>
</tr>
</tbody>
</table>

**Table 3.11: Key Parameter Behaviour when lamps were Supplied using Harmonic Test Waveform 2**

(expressed as a Percentage of Undistorted 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>I RMS</th>
<th>DPF</th>
<th>I Fund</th>
<th>Total Harmonic Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum</strong> (% of Undistorted 230 V Value)</td>
<td>98</td>
<td>98</td>
<td>91</td>
<td>103</td>
</tr>
<tr>
<td><strong>Average</strong> (% of Undistorted 230 V Value)</td>
<td>105</td>
<td>99</td>
<td>98</td>
<td>109</td>
</tr>
<tr>
<td><strong>Maximum</strong> (% of Undistorted 230 V Value)</td>
<td>110</td>
<td>101</td>
<td>103</td>
<td>131</td>
</tr>
</tbody>
</table>
Examination of the data presented in Tables 3.10 and 3.11 indicates that lamp behaviour for RMS current, DPF and fundamental current is not strongly influenced by distortion of the input voltage. For these parameters, results when the lamps were supplied with distorted input voltages are within 10% of the values obtained when undistorted voltages were used and the bulk are within 5%. Total harmonic current can be seen to be slightly more heavily influenced by distortion on the input voltage particularly for harmonic waveform 2. Figures 3.24(a) and 3.24(b) show the variation in total harmonic current for each lamp when supplied with harmonic test waveforms 1 and 2 respectively. Analysis of these figures shows that the large value present for maximum variation in total harmonic current when harmonic test waveform 2 is used to supply the lamp is due to the behaviour of lamp P and represents an outlier.

Figure 3.24(a): Variation of Total Harmonic Current when Lamps were Supplied using Harmonic Test Waveform 1

Figure 3.24(b): Variation of Total Harmonic Current when Lamps were Supplied using Harmonic Test Waveform 2
The impact of distorted input voltages has also been examined on the behaviour of the individual current harmonic orders detailed in Section 3.3.2.1. These variations are shown in Tables 3.12 and 3.13 for harmonic test waveforms 1 and 2 respectively. The tables show that distortion of the input voltage waveform has significant impact on the magnitudes of the individual harmonic current orders. The data in Tables 3.12 and 3.13 is illustrated graphically with more detail in Figures 3.25 – 3.29. In each of these figures part (a) represents the data for harmonic test waveform 1 and part (b) represents the data for harmonic test waveform 2.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>3rd Harmonic</th>
<th>5th Harmonic</th>
<th>7th Harmonic</th>
<th>15th Harmonic</th>
<th>21st Harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (% of Undistorted 230 V Value)</td>
<td>80</td>
<td>59</td>
<td>85</td>
<td>77</td>
<td>107</td>
</tr>
<tr>
<td>Average (% of Undistorted 230 V Value)</td>
<td>86</td>
<td>80</td>
<td>143</td>
<td>131</td>
<td>128</td>
</tr>
<tr>
<td>Maximum (% of Undistorted 230 V Value)</td>
<td>113</td>
<td>102</td>
<td>202</td>
<td>148</td>
<td>193</td>
</tr>
</tbody>
</table>
Table 3.13: Individual Harmonic Current Behaviour when lamps were Supplied using 
Harmonic Test Waveform 2 
(expressed as a Percentage of Undistorted 230 V Values)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>3rd Harmonic</th>
<th>5th Harmonic</th>
<th>7th Harmonic</th>
<th>15th Harmonic</th>
<th>21st Harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% of Undistorted 230 V Value)</td>
<td>68</td>
<td>56</td>
<td>119</td>
<td>125</td>
<td>117</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% of Undistorted 230 V Value)</td>
<td>75</td>
<td>82</td>
<td>185</td>
<td>147</td>
<td>139</td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% of Undistorted 230 V Value)</td>
<td>120</td>
<td>115</td>
<td>248</td>
<td>160</td>
<td>298</td>
</tr>
</tbody>
</table>

Figure 3.25(a): Variation of 3rd Harmonic Current when Lamps were Supplied using 
Harmonic Test Waveform 1

Figure 3.25(b): Variation of 3rd Harmonic Current when Lamps were Supplied using 
Harmonic Test Waveform 2
Figure 3.26(a): Variation of 5th Harmonic Current when Lamps are Supplied using Harmonic Test Waveform 1

Figure 3.26(b): Variation of 5th Harmonic Current when Lamps are Supplied using Harmonic Test Waveform 2

Figure 3.27(a): Variation of 7th Harmonic Current when Lamps are Supplied using Harmonic Test Waveform 1

Figure 3.27(b): Variation of 7th Harmonic Current when Lamps are Supplied using Harmonic Test Waveform 2

Figure 3.28(a): Variation of 15th Harmonic Current when Lamps are Supplied using Harmonic Test Waveform 1

Figure 3.28(b): Variation of 15th Harmonic Current when Lamps are Supplied using Harmonic Test Waveform 2
3.4 Summary

The electrical performance characteristics of 25 CFLs of different brand, construction and price levels have been examined in this chapter. When tested using an undistorted 230 V RMS input voltage source, most CFLs are a highly non-linear load characterised by highly distorted input current waveforms and high input current THD. The strong exception to this is the performance of the high power factor CFL which showed performance which was considerably superior in terms of harmonic content compared to those of all other CFLs which were tested. For power factor, in general, the CFLs were found to have high displacement power factor, but poor true power factor. Overall, the performance of the CFL can be quite different to that of the traditional switch mode power supply. The power supply is characterised by high low order harmonics which decay rapidly as harmonic order increases while many CFLs are characterised by significant levels of harmonic current up to very high orders; in some cases as high as the 49th order (limit of measurement).

The CFLs were also tested for compliance with the Australian Standard governing harmonic emissions for these appliances, IEC61000.3.2 [9]. Of the 25 CFLs tested only one, lamp P, complied with the first clause of the standard based on strict power-related harmonic limits. When tested to the second, less stringent clause, 18 (72%) of the CFLs complied. This left 7 (28%) lamps which failed to comply with the standard outright.
The CFLs were also subjected to varying input voltage magnitudes as well as background distortion levels. Variation of the input voltage was found to have little impact on the input current characteristics of the CFL for the majority of CFLs. For RMS current, displacement power factor and fundamental current, values for all lamps were found to be within ±6% of 230 V values. For total harmonic current, values were also found to be close to those seen when the lamps are supplied at 230 V RMS. The exception to this is the high power factor CFL which showed strong sensitivity in total harmonic current when input voltage magnitude was varied. The impact of variation of the input voltage magnitude on individual dominant harmonic orders has also been examined. With the exception of the high power factor lamp, variation was again found to be small.

For tests which examined the impact of distortion of the input voltage waveform, similar results were found to those seen for voltage variation for basic parameters such as RMS current, displacement power factor and fundamental current, in that the impact is relatively insignificant. However, when distortion was added to the input voltage waveform, the variation of individual dominant harmonic components was considerable, and much larger than that seen when the undistorted voltage magnitude was varied.

The CFL operating characteristics identified in this chapter are essential for the development of an accurate CFL model which will be incorporated into models of the domestic load utilised in this thesis.
CHAPTER 4: ELECTRICAL PERFORMANCE AND CHARACTERISTICS OF MODERN DOMESTIC LOADS

4.1 Introduction

In order to understand and quantify the potential impacts of modern domestic loads on electricity network power quality, it is necessary to understand the electrical characteristics of such loads. Chapter 2 of this thesis examined the developments in relation to domestic loads over the past 10 years and it was shown that there have been significant changes in appliance types, power usage magnitudes and characteristics. Obvious examples of the changes include replacement of traditional televisions with LCD and plasma screens, massive growth in air conditioner penetration and the emergence of the personal computer.

This chapter explores the electrical performance of modern domestic loads other than the CFL which was given special attention in the previous chapter. Performance characteristics examined include power consumption and input current characteristics. This examination is achieved through a series of laboratory tests designed to assess the characteristics of loads over a range of operating conditions. The results from the testing described in this chapter will be used to develop domestic load models which can be employed to quantify their impact of on distribution network power quality.

4.2 Appliances Examined in this Chapter

There are many different types of appliances utilised in domestic residences and it is not feasible to characterise the performance of all of them. Consequently, the appliances examined in this chapter are restricted to those found in the majority of domestic residences and those of significant power usage or hours of operation. Many miscellaneous and small power devices have not been examined as these devices may be rare or rarely used. Such devices include battery chargers (e.g. mobile phone chargers), welders and printers. The data presented in [11] provides an indication of the penetration (numbers of each appliance in each residence) of
various domestic load types and it is from this reference that decisions as to the
devices to be characterised have been made.

The loads in domestic residences can be approximately divided into three electrical
characteristic categories. These are resistive loads, refrigeration loads or other motor
loads (e.g. ceiling fans) and electronic loads. The performance of simple resistive
loads under varying input voltage conditions is well defined and hence laboratory
testing is not required. Based on the remaining two categories, the appliances
examined in this chapter are:

- Refrigeration and Motor Loads
  - 268 L refrigerator
  - Portable air conditioner

- Electronic Loads
  - Home entertainment devices; televisions and DVD players
  - Inverter air conditioner
  - Personal computer and monitor

4.3 Laboratory Testing Methodology

4.3.1 Test Equipment

The same test equipment was utilised for testing the domestic appliances as was used
for the CFL testing. This equipment was described was Section 3.2.3.

4.3.2 Test Schedules

In order to effectively model appliances it is necessary to gain an understanding of
their input current characteristics over the range of input voltages likely to be
encountered when connected to the electricity distribution network. Voltage
magnitude levels change based on loading and the location of a consumer with
respect to the distribution transformer. In practice, there are also varying levels of
voltage distortion present in the supply. Both voltage magnitude changes and
harmonic distortion may have an effect on the input current characteristics of appliances connected to the distribution network.

To gain an understanding of appliance input current characteristics over a range of different input voltages (both magnitude and distortion level), which are termed influence factors, each appliance under test was subjected to a number of scenarios to determine performance under a range of conditions likely to be experienced on Australian electricity distribution networks. To achieve this, each appliance was subjected to the same test as applied to the CFLs described in Chapter 3. These test schedules were described in Section 3.2.2.

4.3.3 Test Procedure and Application of Tests Levels

In all cases, appliances were tested under normal operating conditions. The testing procedure for all appliance tests was as follows:

- At the commencement of each testing period, the appliance were first stabilised at 230 V for 10 minutes before any test voltage levels were applied.
- Once the appliances were stabilised, the test voltage level was applied for a further five minutes to allow the appliance to stabilise at the test level.
- Measurements were then taken using the Hioki 3196 power quality monitor over a two minute period. The measuring instrument was configured to log voltage (fundamental and harmonics to the 50th order plus THD), current (fundamental and harmonics to the 50th order plus THD) and power parameters (real, active and non-active power and displacement power factor) at one second intervals.

4.3.4 Analysis of Test Data

Each steady state test resulted in two minutes of data at taken one second intervals, i.e. 120 samples. This data was reduced as follows:

- The first reading was discarded as it corresponds to a transient period where the instrument is beginning measurement and may not be reliable.
- The next 60 readings were retained
• All other readings were discarded as it was observed that operation after taking 60 readings was static and no further useful information would be obtained from the remaining readings.

This resulted in 60 readings for each test. These readings were then arithmetically averaged and the result used as the characteristic level for further analysis.

4.4 Performance with Undistorted 230 V RMS Input Voltages

4.4.1 268 L Refrigerator

Refrigerators are found in 99.9% of domestic premises [10]. The refrigerator tested was a 268 L refrigerator with freezer. Figure 4.1 shows the input current waveform drawn by the refrigerator when supplied by an undistorted 230 V RMS input voltage. The figure shows that the input current waveform is relatively sinusoidal.

![268 L Refrigerator Input Current Waveform for Undistorted 230 V RMS Input Voltage](image)

Figure 4.1: 268 L Refrigerator Single Cycle Input Current Waveform when Supplied by an Undistorted 230V Input Voltage (50 Hz Fundamental Frequency)

Figure 4.2 shows the input current harmonic spectrum, normalised using the fundamental current, for the refrigerator for an undistorted 230 V RMS input voltage. Low odd order harmonics dominate but fall away quickly as harmonic order
increases. 3rd harmonic is the dominant order with a value of approximately 13% of fundamental current. There is also a noteworthy level of 2nd harmonic.

Table 4.1 shows the basic operating characteristics of the refrigerator when supplied with an undistorted 230 V RMS input voltage.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I RMS (A)</td>
<td>0.66</td>
</tr>
<tr>
<td>P (W)</td>
<td>113.13</td>
</tr>
<tr>
<td>S (VA)</td>
<td>152.08</td>
</tr>
<tr>
<td>Q (var)</td>
<td>101.9</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>0.74 (Lagging)</td>
</tr>
<tr>
<td>THD (% of fundamental)</td>
<td>16.75</td>
</tr>
</tbody>
</table>

4.4.2 Portable Air Conditioner

While modern, split-system air conditioners are generally inverter types, many residences still have older style wall mounted air conditioners which operate using basic refrigeration technology. While portable, the 1.33 kW air conditioner tested here uses the same technology. Figure 4.3 shows the input current waveform for this device when supplied by an undistorted 230 V RMS input voltage.
Figure 4.3: Portable Air Conditioner Single Cycle Input Current Waveform when Supplied by an Undistorted 230 V RMS Input Voltage (50 Hz Fundamental Frequency)

Figure 4.4 shows the input current harmonic spectrum for the portable air conditioner. When an FFT is applied to the waveform seen in Figure 4.3, the half cycle asymmetry produces the even order harmonics seen in Figure 4.4. In fact, the 2\textsuperscript{nd} harmonic is the dominant order which is highly unusual in domestic appliances. For other harmonic orders, levels are low and harmonic current values are negligible for orders other than the 3\textsuperscript{rd}.

Table 4.2 shows the basic operating characteristics of the portable air conditioner.
Table 4.2: Portable Air Conditioner Basic Electrical Characteristics when Supplied by an Undistorted 230 V RMS Input Voltage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I RMS (A)</td>
<td>5.70</td>
</tr>
<tr>
<td>P (W)</td>
<td>1284.63</td>
</tr>
<tr>
<td>S (VA)</td>
<td>1312.15</td>
</tr>
<tr>
<td>Q (var)</td>
<td>267.00</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>0.98 (lagging)</td>
</tr>
<tr>
<td>I THD (% of fundamental)</td>
<td>16.53</td>
</tr>
</tbody>
</table>

4.4.3 Inverter Split System Air Conditioner

Investigation of manufacturer data reveals that almost all modern split system air conditioners are now inverter type. The split-system air conditioner tested was a 3.3 kW inverter unit. The unit was tested with the compressor running at all times. Figure 4.5 shows the input current waveform drawn by the air conditioner when supplied by an undistorted 230 V RMS voltage input. The waveform is nearly sinusoidal indicating that the unit does not draw significant harmonic currents. This is verified in Figure 4.6 which shows the input current harmonic spectrum of air conditioner normalised using the fundamental current. This is a slightly unexpected result given that the inverter is a power electronic load which contains a single phase rectifier and that first generation inverter air conditioners are known to draw highly distorted current waveforms [20]. The results here indicate that steps have been taken by the air conditioner manufacturer to mitigate harmonic currents.
Table 4.3 shows the basic operating characteristics of the air conditioner for an undistorted 230 V RMS input voltage.
Table 4.3: 3.3 kW Inverter Air Conditioner Basic Electrical Characteristics when Supplied by an Undistorted 230 V RMS Input Voltage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I RMS (A)</td>
<td>11.13</td>
</tr>
<tr>
<td>P (W)</td>
<td>2557.62</td>
</tr>
<tr>
<td>S (VA)</td>
<td>2560.08</td>
</tr>
<tr>
<td>Q (var)</td>
<td>112.18</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>1.00</td>
</tr>
<tr>
<td>I THD (% of fundamental)</td>
<td>3.43</td>
</tr>
</tbody>
</table>

4.4.4 Televisions

One or more televisions are present in almost every domestic premises [11]. Television technology has undergone considerable change in the past decade with traditional CRT technology being replaced by plasma and LCD technologies which offer larger screen sizes. Three televisions have been subjected to laboratory testing. These televisions represent the most common screen technologies. The televisions tested are a 51 cm CRT television, a 32 inch (approximately 82cm) plasma screen television and a 32 inch LCD television.

Figure 4.7 shows the input current waveform for the 51 cm CRT television when supplied by an undistorted 230 V RMS input voltage, while Figure 4.8 shows the input current waveform for the plasma television and Figure 4.9 shows the input current waveform for the LCD television. These show that the CRT type television draws a current waveform similar to that of a single phase rectifier. In terms of input current waveform shape, the figures show that while still distorted, the waveforms for the plasma and LCD televisions are considerably more sinusoidal than that of the CRT television. Given that the power supplies of almost all televisions are of switch mode type which have the same basic characteristics, it is evident that the more modern televisions incorporate technology to reduce harmonic current distortion.
Figure 4.7: 51 cm CRT Television Single Cycle Input Current Waveform when Supplied by an Undistorted 230 V RMS Input Voltage (50 Hz Fundamental Frequency)

Figure 4.8: 32 Inch Plasma Screen Television Current Waveform for Undistorted 230 V RMS Input Voltage

51 cm CRT Television Current Waveform for Undistorted 230 V RMS Input Voltage

32 Inch Plasma Screen Television Current Waveform for Undistorted 230 V RMS Input Voltage
Figure 4.9: 32 Inch LCD Television Single Cycle Input Current Waveform when Supplied by an Undistorted 230 V RMS Input Voltage (50 Hz Fundamental Frequency)

Figures 4.10, 4.11 and 4.12 show the input current harmonic spectrums normalised using the respective fundamental current for the CRT, plasma and LCD televisions.

Figure 4.10: 51 cm CRT Television Normalised Current Harmonic Spectrum when Supplied by an Undistorted 230 V RMS Input Voltage
Further, Figure 4.10 shows that the CRT displays harmonic performance characteristic of the traditional single phase rectifier which often forms the input stage of the switch mode power supply. The harmonic spectrum is characterised by very high odd order harmonic current levels for low order harmonic which fall away quickly with harmonic order. Figures 4.11 and 4.12 show that the performance of the plasma and LCD type televisions is similar, with the LCD television performing slightly better than the plasma television. The harmonic spectrums for both televisions are characterised by high values for low order odd harmonics, whilst levels above the 9th order are small.

Comparison of Figures 4.10 – 4.12 indicate that the harmonic current performance of the CRT technology television is significantly worse than that observed for the plasma screen television. Further, comparisons of the harmonic current drawn by each television expressed in amperes, as shown in Figure 4.13, shows that in spite of
the plasma screen television having a much higher rated power than the CRT
televisions, the magnitudes of the harmonic currents are greater for the CRT
televisions than for the plasma screen television. This is an unexpected result as it
has often been assumed that higher harmonic currents would accompany the higher
fundamental power consumption of the larger new technology screens.

![Comparison of Television Harmonic Currents](image)

**Figure 4.13: Comparison of the Harmonic Currents Drawn by the Three Televisions Tested**

Table 4.4 shows the basic electrical characteristics for each of the televisions tested. It
further shows that the plasma screen draws significantly more active power than the CRT televisions, however, the current and apparent power drawn by the 51cm CRT television is greater due to the harmonic content.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CRT</th>
<th>Plasma</th>
<th>LCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>I RMS (A)</td>
<td>0.53</td>
<td>0.50</td>
<td>0.32</td>
</tr>
<tr>
<td>P (W)</td>
<td>58.88</td>
<td>103.68</td>
<td>65.36</td>
</tr>
<tr>
<td>S (VA)</td>
<td>120.86</td>
<td>115.20</td>
<td>73.23</td>
</tr>
<tr>
<td>Q (var)</td>
<td>105.54</td>
<td>49.60</td>
<td>32.51</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>1.00</td>
<td>-0.90</td>
<td>-0.91</td>
</tr>
<tr>
<td>I THD (% of fundamental)</td>
<td>178.21</td>
<td>34.03</td>
<td>18.92</td>
</tr>
</tbody>
</table>

**4.4.5 Personal Computer (PC)**

Computer penetration has increased from negligible levels to approximately 70% (i.e. 7 in every 10 residences have a PC) since 1994 [10]. The computer tested was a
Pentium 4 1.6 GHz PC. The PC was tested in on-mode without hard disk drive activity. Figure 4.14 shows the input current waveform for this device when supplied by an undistorted 230 V RMS input voltage. The current waveform is characteristic of a single phase rectifier. The input current harmonic spectrum shown in Figure 4.15 for the PC is also characteristic of a single phase rectifier. This spectrum is characterised by very high low order odd harmonics.
Table 4.5 shows the basic electrical characteristics of the Pentium 4 PC when supplied by an undistorted 230 V input voltage. Of note is the very high harmonic current THD.

**Table 4.5: PC Basic Electrical Characteristics when Supplied by an Undistorted 230V Input Voltage**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I RMS (A)</td>
<td>0.57</td>
</tr>
<tr>
<td>P (W)</td>
<td>58.64</td>
</tr>
<tr>
<td>S (VA)</td>
<td>130.87</td>
</tr>
<tr>
<td>Q (var)</td>
<td>117.00</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>1</td>
</tr>
<tr>
<td>I THD (% of fund)</td>
<td>196.49</td>
</tr>
</tbody>
</table>

4.4.6 17 Inch LCD Monitor

Almost all modern PC monitors are now of the LCD type. A 17 inch LCD monitor has been tested with the connected PC running off a separate supply. The input current waveform for the monitor when supplied with an undistorted 230 V RMS input voltage applied is shown in Figure 4.16.

![17 Inch LCD Monitor Current Waveform for Undistorted 230 V RMS Input Voltage](image)

**Figure 4.16: 17 Inch LCD Monitor Single Cycle Input Current Waveform when Supplied by an Undistorted 230 V RMS Input Voltage (50 Hz Fundamental Frequency)**
Figure 4.16 shows that the monitor has a typical single phase rectifier current waveform. Figure 4.17 shows the normalised input current harmonic spectrum for the monitor for an undistorted 230 V RMS voltage input. Once again, the current harmonic spectrum is typical of equipment supplied by a single phase rectifier.

Table 4.6 shows the basic electrical characteristics of the LCD monitor when supplied with an undistorted 230 V RMS input voltage. Harmonic current THD is seen to be high, however, power consumption is small.

4.4.7 DVD Player

DVD players have almost exclusively replaced traditional VCRs. Figure 4.18 shows the input current waveform for the DVD player when supplied with an undistorted 230 V RMS input voltage. The waveform is characteristic of a simple, single-phase rectifier.
Figure 4.19 shows the normalised input current harmonic spectrum for the DVD player when supplied with an undistorted 230 V RMS voltage input. The current spectrum observed is similar to that of a simple single phase rectifier, however, the high order harmonics present in this spectrum are somewhat higher than may be expected for the simple rectifier.

Table 4.7 shows the basic electrical characteristics of the DVD player when supplied by an undistorted 230 V RMS input voltage. The current THD level is extremely high, however, power consumption is very low.
Table 4.7: DVD Player Basic Electrical Characteristics when Supplied by an Undistorted 230 V RMS Input Voltage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I RMS (A)</td>
<td>0.09</td>
</tr>
<tr>
<td>P (W)</td>
<td>7.44</td>
</tr>
<tr>
<td>S (VA)</td>
<td>19.87</td>
</tr>
<tr>
<td>Q (var)</td>
<td>18.41</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>-0.37 (leading)</td>
</tr>
<tr>
<td>I THD (% of fund)</td>
<td>241.99</td>
</tr>
</tbody>
</table>

4.5 Performance with Varying Input Voltages

As described in Section 4.3.2, each of the appliances has also been tested to determine the impact of variations in the magnitude and harmonic distortion levels of the input voltage.

4.5.1 Variation of Input Voltage Magnitude

Two tests were performed to assess the impact of variations in the magnitude of the supply voltage on the electrical operating characteristics of the appliances under test. The first test involved application of a 253 V RMS input voltage. This voltage is at the upper end of the Australian nominal low voltage range (230 + 10 %). The second test involved application of a 207 V RMS voltage. The voltage 207 V is beyond the lower end of the Australian distribution system nominal low voltage range (230 – 6%), however, it is within the nominal utilisation range of 230 V – 11 % (given the 5 % voltage drop permitted in an installation).

Table 4.8 shows the results of the first test for the basic parameters of RMS current (I RMS), displacement power factor (DPF), fundamental current (I Fund) and total harmonic current. In order to easily identify the difference between this test and the results obtained using the undistorted nominal (230 V RMS), the values in Table 4.8 are expressed as a percentage of the values obtained when an input voltage of 230 V RMS was used.
Table 4.8: Variation in Basic Parameters when Appliances were Supplied by an Undistorted 253 V RMS Input Voltage

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I RMS (% of 230 V Value)</th>
<th>DPF (% of 230 V Value)</th>
<th>I Fund (% of 230 V Value)</th>
<th>Total Harmonic Current (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>107</td>
<td>100</td>
<td>111</td>
<td>106</td>
</tr>
<tr>
<td>LCD TV</td>
<td>110</td>
<td>103</td>
<td>111</td>
<td>98</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>102</td>
<td>101</td>
<td>104</td>
<td>88</td>
</tr>
<tr>
<td>DVD Player</td>
<td>106</td>
<td>100</td>
<td>111</td>
<td>103</td>
</tr>
<tr>
<td>Portable AC</td>
<td>109</td>
<td>100</td>
<td>110</td>
<td>87</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>111</td>
<td>100</td>
<td>111</td>
<td>88</td>
</tr>
<tr>
<td>PC</td>
<td>104</td>
<td>100</td>
<td>108</td>
<td>103</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>105</td>
<td>100</td>
<td>110</td>
<td>103</td>
</tr>
</tbody>
</table>

Figures 4.20 – 4.23 shows the data in Table 4.9 graphically.

Figure 4.20: Variation in RMS Current when Appliances were Supplied by an Undistorted 253 V RMS Input Voltage
Figure 4.21: Variation in Displacement Power Factor when Appliances were Supplied by an Undistorted 253 V RMS Input Voltage

Figure 4.22: Variation in Fundamental Current when Appliances were Supplied by an Undistorted 253 V RMS Input Voltage
The data in Table 4.9 and Figures 4.20 – 4.23 shows that there is relatively small variation in RMS current and displacement power factor when the appliances are supplied at 253 V RMS as opposed to 230 V RMS. The variation in fundamental current and total harmonic current is larger than that seen for RMS current and displacement power factor but is still modest with the maximum variation being a 13% decrease as seen for total harmonic current for the portable air conditioner.

The relationship between the input voltage magnitude and individual harmonic current orders has also been investigated. Five harmonic orders have been identified for investigation; 3rd, 5th, 7th, 15th and 21st. The 3rd, 5th and 7th are selected as these are the dominant harmonic orders observed in low voltage networks. The 15th and 21st are selected as these are orders which coincide with typical ripple injection load control signal frequencies which have been a subject of focus in all investigations so far and will ultimately be the subject of further investigation in following chapters of this thesis. Table 4.9 shows the results for the aforementioned harmonic orders when the appliances under test were supplied with a 253 V RMS input voltage. In Table 4.9, values are expressed as a percentage of the value obtained when the appliance was supplied with an undistorted 230 V RMS input voltage.
Table 4.9 indicates that although the variations in the basic parameters seen in Table 4.8 were relatively small, this does not preclude large variation in individual harmonic orders. The table shows that the variations for the low order harmonics 3\textsuperscript{rd} and 5\textsuperscript{th} are relatively modest. As the harmonic order increases, the variation from the 230 V RMS values becomes considerably larger. In the most extreme case, the magnitude of the 21\textsuperscript{st} harmonic for the 51 cm CRT television is more than double the corresponding magnitude obtained when a 230 V RMS input voltage was applied.

**Table 4.9: Variation in Individual Harmonic Orders when Appliances were Supplied by an Undistorted 253 V RMS Input Voltage**

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I\textsubscript{3} (% of 230 V Value)</th>
<th>I\textsubscript{5} (% of 230 V Value)</th>
<th>I\textsubscript{7} (% of 230 V Value)</th>
<th>I\textsubscript{15} (% of 230 V Value)</th>
<th>I\textsubscript{21} (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>110</td>
<td>109</td>
<td>107</td>
<td>84</td>
<td>237</td>
</tr>
<tr>
<td>LCD TV</td>
<td>97</td>
<td>109</td>
<td>104</td>
<td>68</td>
<td>137</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>92</td>
<td>107</td>
<td>57</td>
<td>107</td>
<td>43</td>
</tr>
<tr>
<td>DVD Player</td>
<td>110</td>
<td>109</td>
<td>107</td>
<td>93</td>
<td>88</td>
</tr>
<tr>
<td>Portable AC</td>
<td>93</td>
<td>176</td>
<td>65</td>
<td>114</td>
<td>68</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>87</td>
<td>85</td>
<td>85</td>
<td>97</td>
<td>121</td>
</tr>
<tr>
<td>PC</td>
<td>107</td>
<td>106</td>
<td>105</td>
<td>92</td>
<td>73</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>109</td>
<td>107</td>
<td>105</td>
<td>84</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 4.10 shows the results of the second test, 207 V RMS input voltage magnitude, for the basic parameters of RMS current (I RMS), displacement power factor (DPF), fundamental current (I Fund) and total harmonic current. The values in Table 4.10 are expressed as a percentage of the values obtained when an input voltage of 230 V RMS was used.
Table 4.10: Variation in Basic Parameters when Appliances were Supplied by an Undistorted 207 V RMS Input Voltage

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I RMS (% of 230 V Value)</th>
<th>DPF (% of 230 V Value)</th>
<th>I Fund (% of 230 V Value)</th>
<th>Total Harmonic Current (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>92</td>
<td>100</td>
<td>88</td>
<td>93</td>
</tr>
<tr>
<td>LCD TV</td>
<td>93</td>
<td>96</td>
<td>92</td>
<td>106</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>105</td>
<td>100</td>
<td>103</td>
<td>121</td>
</tr>
<tr>
<td>DVD Player</td>
<td>99</td>
<td>100</td>
<td>93</td>
<td>98</td>
</tr>
<tr>
<td>Portable AC</td>
<td>100</td>
<td>98</td>
<td>100</td>
<td>123</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>89</td>
<td>100</td>
<td>89</td>
<td>112</td>
</tr>
<tr>
<td>PC</td>
<td>94</td>
<td>99</td>
<td>93</td>
<td>95</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>95</td>
<td>100</td>
<td>91</td>
<td>96</td>
</tr>
</tbody>
</table>

The values in Table 4.10 and Figures 4.24 – 4.27 show a similar trend to those observed in Table 4.8 and Figures 4.20 – 4.23. However, the variations observed for this test is somewhat larger than that seen for the first test. Again, variation in RMS current and displacement power factor is small. Variation in fundamental current and total harmonic current is larger but generally relatively small.

Figure 4.24: Variation in RMS Current when Appliances were Supplied by an Undistorted 207 V RMS Input Voltage
Figure 4.25: Variation in Displacement Power Factor when Appliances were Supplied by an Undistorted 207 V RMS Input Voltage

Figure 4.26: Variation in Fundamental Current when Appliances were Supplied by an Undistorted 207 V RMS Input Voltage
Table 4.11 shows the variation in harmonic current for selected harmonic orders when the appliances were supplied with a 207 V RMS input voltage. Similar results are observed to those recorded in Table 4.9. The variation in low order harmonic currents is relatively small, however, as the harmonic order increases, variations become considerably larger.
Table 4.11: Variation in Individual Harmonic Orders when Appliances were Supplied by an Undistorted 207 V RMS Input Voltage

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I3 (% of 230 V Value)</th>
<th>I5 (% of 230 V Value)</th>
<th>I7 (% of 230 V Value)</th>
<th>I15 (% of 230 V Value)</th>
<th>I21 (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>88</td>
<td>89</td>
<td>91</td>
<td>111</td>
<td>362</td>
</tr>
<tr>
<td>LCD TV</td>
<td>101</td>
<td>99</td>
<td>91</td>
<td>125</td>
<td>142</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>117</td>
<td>104</td>
<td>75</td>
<td>156</td>
<td>131</td>
</tr>
<tr>
<td>DVD Player</td>
<td>93</td>
<td>93</td>
<td>94</td>
<td>101</td>
<td>106</td>
</tr>
<tr>
<td>Portable AC</td>
<td>156</td>
<td>232</td>
<td>125</td>
<td>136</td>
<td>124</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>113</td>
<td>119</td>
<td>115</td>
<td>80</td>
<td>76</td>
</tr>
<tr>
<td>PC</td>
<td>92</td>
<td>93</td>
<td>93</td>
<td>99</td>
<td>110</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>91</td>
<td>92</td>
<td>94</td>
<td>107</td>
<td>139</td>
</tr>
</tbody>
</table>

4.5.2 Variation in Input Voltage Harmonic Distortion

Two tests were carried out to assess the impact of variations in harmonic distortion of the input voltage to the appliances. These tests involved the application of the two harmonic test waveforms described in Section 3.2.2 of Chapter 3. The fundamental voltage magnitude for both waveforms was 230 V.

Table 4.12 and Figures 4.28 – 4.31 show the variation in RMS current (I RMS), displacement power factor (DPF), fundamental current (I Fund) and total harmonic current between the base case (undistorted 230 V RMS input voltage) and the case for harmonic test waveform 1 input voltage. The values in Table 4.12 are expressed as a percentage of the values obtained when an input voltage of 230V RMS was used.
Table 4.12: Variation in Basic Parameters when Appliances were Supplied using Harmonic Test Waveform 1

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I RMS (% of 230 V Value)</th>
<th>DPF (% of 230 V Value)</th>
<th>I Fund (% of 230 V Value)</th>
<th>Total Harmonic Current (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>67</td>
<td>100</td>
<td>90</td>
<td>59</td>
</tr>
<tr>
<td>LCD TV</td>
<td>100</td>
<td>101</td>
<td>100</td>
<td>111</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>117</td>
<td>100</td>
<td>119</td>
<td>102</td>
</tr>
<tr>
<td>DVD Player</td>
<td>75</td>
<td>100</td>
<td>103</td>
<td>67</td>
</tr>
<tr>
<td>Portable AC</td>
<td>107</td>
<td>100</td>
<td>107</td>
<td>138</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>105</td>
<td>100</td>
<td>105</td>
<td>147</td>
</tr>
<tr>
<td>PC</td>
<td>78</td>
<td>101</td>
<td>101</td>
<td>71</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>70</td>
<td>100</td>
<td>99</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 4.28: Variation in RMS Current when Appliances were Supplied using Harmonic Test Waveform 1
Figure 4.29: Variation in Displacement Power Factor when Appliances were Supplied using Harmonic Test Waveform 1

Figure 4.30: Variation in Fundamental Current when Appliances were Supplied using Harmonic Test Waveform 1
Table 4.13 and Figures 4.28 and 4.29 indicate that there is little variation in displacement power factor and fundamental current when the appliances are supplied with harmonic test waveform 1. However, considerable variation is observed for RMS current and total harmonic current. Further, the variations are much larger than those observed for the tests where input voltage magnitude was varied. This indicates that appliance input current is more sensitive to changes in input voltage distortion, specifically, changes in the peak voltage due to waveform flattening as opposed to changes in input RMS voltage magnitude.

Table 4.13 shows the variation in individual harmonic orders when harmonic test waveform 1 is applied to the appliances under test. The table shows that there is considerable variation in all harmonic orders including an extremely large variation in 5th harmonic current for the portable air conditioner. The very large variation in 5th harmonic current seen for the portable air does not appear to be a measurement problem. Instead, it appears that this device is highly sensitive to changes in 5th harmonic voltage levels.
Table 4.1: Variation in Individual Harmonic Orders when Appliances were Supplied using Harmonic Test Waveform 1

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I3 (% of 230 V Value)</th>
<th>I5 (% of 230 V Value)</th>
<th>I7 (% of 230 V Value)</th>
<th>I15 (% of 230 V Value)</th>
<th>I21 (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>80</td>
<td>63</td>
<td>41</td>
<td>65</td>
<td>141</td>
</tr>
<tr>
<td>LCD TV</td>
<td>87</td>
<td>191</td>
<td>85</td>
<td>112</td>
<td>126</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>97</td>
<td>228</td>
<td>75</td>
<td>114</td>
<td>74</td>
</tr>
<tr>
<td>DVD Player</td>
<td>89</td>
<td>62</td>
<td>30</td>
<td>87</td>
<td>60</td>
</tr>
<tr>
<td>Portable AC</td>
<td>82</td>
<td>3240</td>
<td>202</td>
<td>157</td>
<td>95</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>69</td>
<td>326</td>
<td>116</td>
<td>96</td>
<td>99</td>
</tr>
<tr>
<td>PC</td>
<td>95</td>
<td>83</td>
<td>66</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>88</td>
<td>66</td>
<td>37</td>
<td>68</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 4.14 and Figures 4.32 – 4.35 show the variation in RMS current (I RMS), displacement power factor (DPF), fundamental current (I Fund) and total harmonic current between the base case (undistorted 230 V RMS input voltage) and the case for harmonic test waveform 2 input voltage. The values in Table 4.15 are expressed as a percentage of the values obtained when an input voltage of 230 V RMS was used.

Similar results are observed as those obtained when harmonic test waveform 1 was used to supply the appliance; variation in displacement power factor and fundamental current is modest, however, variation in RMS current and total harmonic current is significant.
Table 4.1: Variation in Basic Parameters when Appliances were Supplied using Harmonic Test Waveform 2

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I RMS (% of 230 V Value)</th>
<th>DPF (% of 230 V Value)</th>
<th>I Fund (% of 230 V Value)</th>
<th>Total Harmonic Current (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>79</td>
<td>100</td>
<td>96</td>
<td>73</td>
</tr>
<tr>
<td>LCD TV</td>
<td>103</td>
<td>101</td>
<td>103</td>
<td>118</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>122</td>
<td>101</td>
<td>124</td>
<td>96</td>
</tr>
<tr>
<td>DVD Player</td>
<td>87</td>
<td>101</td>
<td>102</td>
<td>83</td>
</tr>
<tr>
<td>Portable AC</td>
<td>106</td>
<td>100</td>
<td>105</td>
<td>161</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>105</td>
<td>100</td>
<td>105</td>
<td>176</td>
</tr>
<tr>
<td>PC</td>
<td>87</td>
<td>101</td>
<td>99</td>
<td>84</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>80</td>
<td>94</td>
<td>98</td>
<td>75</td>
</tr>
</tbody>
</table>

Figure 4.32: Variation in RMS Current when Appliances were Supplied using Harmonic Test Waveform 2
Figure 4.33: Variation in Displacement Power Factor when Appliances were Supplied using Harmonic Test Waveform 2

Figure 4.34: Variation in Fundamental Current when Appliances were Supplied using Harmonic Test Waveform 2
Figure 4.35: Variation in Total Harmonic Current when Appliances were Supplied using Harmonic Test Waveform 2

Table 4.15 shows the variation in individual harmonic orders when harmonic test waveform 2 is use to supply them. Again, considerable variation in all harmonics is observed. As was observed in Table 4.13, there is again a very large variation in 5th harmonic levels for the portable air conditioner. Once again, the very large variation in 5th harmonic current seen for the portable air does not appear to be a measurement problem. Instead, it appears that this device is highly sensitive to changes in 5th harmonic voltage levels.
Table 4.15: Variation in Individual Harmonic Orders when Appliances were Supplied using Harmonic Test Waveform 2

<table>
<thead>
<tr>
<th>Appliance</th>
<th>I3 (% of 230 V Value)</th>
<th>I5 (% of 230 V Value)</th>
<th>I7 (% of 230 V Value)</th>
<th>I15 (% of 230 V Value)</th>
<th>I21 (% of 230 V Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51cm CRT TV</td>
<td>70</td>
<td>35</td>
<td>55</td>
<td>43</td>
<td>840</td>
</tr>
<tr>
<td>LCD TV</td>
<td>75</td>
<td>226</td>
<td>116</td>
<td>113</td>
<td>105</td>
</tr>
<tr>
<td>Plasma TV</td>
<td>81</td>
<td>281</td>
<td>74</td>
<td>87</td>
<td>59</td>
</tr>
<tr>
<td>DVD Player</td>
<td>70</td>
<td>21</td>
<td>55</td>
<td>42</td>
<td>151</td>
</tr>
<tr>
<td>Portable AC</td>
<td>133</td>
<td>4306</td>
<td>311</td>
<td>186</td>
<td>107</td>
</tr>
<tr>
<td>Inverter AC</td>
<td>64</td>
<td>404</td>
<td>157</td>
<td>92</td>
<td>100</td>
</tr>
<tr>
<td>PC</td>
<td>86</td>
<td>72</td>
<td>75</td>
<td>59</td>
<td>133</td>
</tr>
<tr>
<td>LCD Monitor</td>
<td>70</td>
<td>34</td>
<td>56</td>
<td>40</td>
<td>204</td>
</tr>
</tbody>
</table>

4.6 Summary

This chapter detailed laboratory testing of a range of modern domestic appliances in order to determine the electrical operating characteristics over a range of input voltages. Based on performance with undistorted rated input voltage, the following are interesting results presented in this chapter:

- Modern televisions (plasma and LCD types) have significantly better performance with respect to harmonic current emission compared to their CRT predecessors in spite of higher rated power.

- Modern inverter air conditioners have harmonic emission performance much better than first generation inverter types.

- The performance of the PC reflects that of a traditional simple switch mode power supply. This is the only relatively high power device to have this characteristic.

- Low power rated devices such as the DVD player appear to be supplied through simple switch mode power supplies.
In practice it is unlikely that appliances connected to electricity networks will be supplied at undistorted nominal voltage levels. Understanding appliances input current characteristics when subjected to input voltages which are realistic is essential for understanding the electrical behaviour of devices connected to the electricity network for the purposes of network planning, modelling and analysis.

The investigations undertaken and reported in this chapter indicate that the basic input current characteristics of the appliances tested are relatively insensitive to changes in the magnitude of the voltage when it is undistorted. Variation of low order individual harmonics between the nominal voltage case and an increased or reduced voltage case were found to be significantly larger than basic quantities such as RMS current or fundamental current. However, for most appliances, the variation was relatively small.

Investigations completed using distorted input voltages indicated that the input current characteristics of most devices were highly sensitive to distortion in the input voltage. Harmonic distortion of the input voltage, specifically changes in the peak voltage due to waveform flattening was found to have a much greater impact on the input current of each appliance than in the case for changes in undistorted supply voltage magnitude.
CHAPTER 5: MODELLING METHODOLOGY FOR SIMULATION OF THE IMPACT OF THE MODERN DOMESTIC LOAD ON ELECTRICITY DISTRIBUTION NETWORK HARMONIC LEVELS

5.1 Introduction

This chapter details the modelling methodology which was developed to examine the impact of modern domestic loads on low voltage (LV) electricity distribution network harmonic voltage levels. The data obtained from the laboratory testing of appliances described in the preceding two chapters was used to develop load models of the domestic appliances of interest. These models were then employed in conjunction with low voltage feeder network models to produce flexible simulation platforms of the load and network. Harmonic voltage levels for a range of network and loading scenarios could be observed using such an exercise.

Modelling of the low voltage network is complex since there will be an unlimited number of loading and network scenarios at any given location or point in time. To deal with this complexity, a range of modelling scenarios have been developed in an attempt to best represent practical operating conditions. These scenarios take into account factors such as the network length and loading conditions. The models which have been developed are not designed to accurately represent or duplicate present operating conditions at any particular site. Instead they have been developed to give insight into the potential future impact of a range of modern domestic appliances, particularly CFLs, on voltage harmonic level when they are connected to typical low voltage distribution networks.

All facets of network system model and load model development and implementation are described in this chapter. This includes the modelling scenarios developed and assumptions with respect to model parameters.

5.2 Basic Modelling Methodology

The developed models were designed to reflect typical practical low voltage networks in terms of network construction and loading levels. Information regarding
typical low voltage feeder details including lengths, conductor types, distribution transformer sizes and impedances and loading levels have been obtained from Endeavour Energy (formerly Integral Energy), an Australian electricity distribution utility. This information was used in the construction of all models developed in this chapter. The loads connected to these network models were developed based on the laboratory characterisation of appliance behaviour described in Chapters 3 and 4.

The models which have been developed provide a flexible and relatively simple means of modelling LV distribution systems in relation to harmonic behaviour. The low voltage network model includes the distribution transformer and downstream feeder impedance but no additional upstream impedance. The network was modelled using lumped series resistances and inductances. Connected to this network model are models of the non-linear (distorting) domestic loads. The loads have been dispersed at regular intervals along the modelled LV feeder. Figure 5.1 shows a section of a modelled feeder indicating the manner in which the models have been constructed.

The distorting loads connected to the network have been modelled using a frequency domain approach to modelling. The method adopted involves application of a current source to inject the harmonic currents relevant to each domestic appliance. Thus a current injection method has been selected as it is a well developed technique for harmonic modelling and is relatively easy to apply. Use of this method requires a distinct model to be developed for each harmonic order and each network or load condition scenario being investigated. The harmonic current injected by each device is modelled separately. This approach has been taken to maintain maximum flexibility within the models.
Five harmonic orders have been selected for detailed investigation and analysis. As stated, the modelling methodology requires distinct models to be constructed for each order. The harmonic orders of interest are $3^{rd}$, $5^{th}$, $7^{th}$, $15^{th}$ and $21^{st}$. The rationale for selecting these orders for special investigation is as follows:

1. The first three harmonic orders represent the dominant voltage harmonic orders currently observed on the low voltage distribution network. Consequently, changes in the magnitude of these harmonics have the potential to lead to problems with harmonic magnitudes at certain sites.

2. The other two harmonic orders were selected as they correlate to harmonic orders which are close to commonly used load control ripple injection frequencies. Electricity distributors use these signals for control of loads such as off peak hot water systems and street lighting. There is concern in the industry that high frequency harmonics, particularly those associated with high penetration of CFL lighting may have an adverse impact on these ripple injection systems including maloperation or non-operation of control relays. Studies such as [12] have identified this as an issue and it is expected that the modelling performed here may give insight as to whether or not the problem is likely to occur on Australian networks.

Further detailed descriptions of the modelling process will be given in the forthcoming sections of this chapter.
5.3 Software Package

The PSCAD/EMTDC software package has been selected to carry out the simulation work. This package has been selected as it is versatile, relatively easy to use and is capable of performing all of the modelling tasks required to study the impact of the domestic loads on the electricity distribution network.

5.4 Modelling Assumptions

It is not feasible to model every different network construction, operation or loading scenario. Consequently, it is necessary to make a number of assumptions regarding network and load operation and behaviour. Each of the assumptions which have been made to simplify the modelling task and the justification for such assumptions is detailed below:

1. **Balanced network operation** - The load on the network has been assumed to be balanced. This allows the use of single phase models.

2. **Neutral conductor** – The neutral conductor is assumed to be of the same material and have the same impedance values as the active conductor. This is common practice in Australian electricity distribution networks.

3. **Feeders are modelled as series resistance and inductance** – overhead feeders are modelled as series resistances and inductances and capacitance is ignored. This is justified since capacitance for short overhead lines can be considered negligible.

4. **Time window** - The time of day for which the models have been developed is assumed to be in the evening. This time of day has been selected as it is believed that it is at this time of day that most domestic non-linear loads will be operating. It is also the period during which the largest amount of lighting and hence CFLs will be operating.

5. **Service and sub-circuit impedance is ignored** – the impedance of the service mains and all other sub-circuit impedances have been ignored. This is justified
because the length of these circuits is short in comparison to the length of the main low voltage feeder.

**6. The network is loaded to capacity** – For each model, it is assumed that the network is loaded to a level approximately equal to the capacity of the distribution transformer. This determines the number of customers connected to the low voltage feeder and in turn the number of loads connected to each network model.

**7. Only overhead networks are considered** – this assumption is justified since the majority of low voltage feeders in Australia are of overhead construction. As the models are designed to represent a typical network, overhead construction was selected. The two main alternatives to overhead construction are underground cable and aerial bundled cable (ABC). ABC is rarely used and as such has not been considered. Use of underground cables is increasing as every new subdivision now has underground distribution of power. However, the models developed here are designed to investigate the worst potential impact of modern devices on harmonic voltage levels. The impedance of underground cables is highly likely to be significantly less than that of overhead lines. Given the impedance difference between overhead and underground feeders and the fact that underground feeders are often shorter than overhead feeders, it is likely that the worst impacts of the harmonic currents due to modern loads will be observed at sites supplied by overhead lines as opposed to underground cables.

**8. Linear loads are ignored** – Linear loads have been ignored in all models developed. This is justified since none of the models operate under resonance conditions where linear load would have a damping effect. In cases where resonance is not present, linear load has negligible impact on harmonic voltage levels.

**9. Diversity is ignored** – Appliance operating diversity, that is, diversity in the number of appliances operating simultaneously, has been ignored. This is justified as the appliances included in the model are highly likely to be operating simultaneously at the time of day for which the model has been developed.
10. Upstream impedance is ignored - The low voltage network is modelled from the distribution transformer and downstream and includes the distribution transformer impedance but no additional upstream impedance. This is a valid approach as the combined upstream impedance is normally insignificant beside that of the distribution transformer impedance for the majority of Australian distribution networks.

5.5 Network Modelling

The distribution network is modelled using actual network parameters obtained from Endeavour Energy. The network models are designed to simulate typical voltage distribution feeder construction. The conductor type used for the network models represents a common type used in Australian electricity distribution networks. The network is modelled using lumped series resistances and inductances. The conductor used for the model is Olex Mercury. This is 111 mm$^2$ All Aluminium Alloy (AAC) conductor. This conductor has the following impedance properties:

- Resistance: 0.315 $\Omega$/km (at 50 Hz, 75 °C)
- Inductive Reactance: 0.259 $\Omega$/km (to 0.3 m at 50 Hz)

Differences in the sequence characteristics of triplen and non-triplen harmonics necessitated construction of different models for triplen and non-triplen harmonic orders. For non-triplen harmonics, the network can be modelled as a simple single phase equivalent. For such models, only the impedance of the active conductor need be modelled as in a balanced system no harmonic current will flow in the neutral conductor.

For triplen harmonics, the neutral impedance must also be modelled as currents from these harmonic orders will add in the neutral. To convert this three-phase interaction into a single phase equivalent the impedance of the neutral conductor must be multiplied by 3 and added to the active conductor impedance. As such the effective impedance used in the single phase equivalent circuit is 4 times the active conductor impedance (given the assumption that the neutral conductor is made out of the same
material as the active conductor). Further details regarding this method of modelling is given in [48].

The model is developed to represent the two circuits emanating from the distribution transformer. Each circuit is of the same length and the loads are distributed evenly along each circuit. The appropriate conductor impedance is connected between each load. Figure 5.3 shows a basic schematic of the model.

![Figure 5.3: Basic Schematic of Low Voltage Feeder Model](image)

5.5.1 Feeder Length Modelling Scenarios

Two scenarios have been considered for low voltage feeder lengths. These correspond to a ‘typical’ or average length and an above average length. Information from Endeavour Energy indicates that 250 m is an appropriate length for an average length overhead low voltage feeder, while 350 m is an appropriate length for an above average length feeder.

5.5.2 Distribution Transformers

For the average feeder length model, the distribution transformer size is 350 kVA. The distribution transformer impedance is 4% on its own base, which is typical for a transformer of this size. The distribution transformer is modelled as a simple inductance. The transformer is assumed to be loaded to rated capacity. Information from Endeavour Energy indicates that such a transformer would supply
approximately 60 distinct customers (i.e. residences) across the three phases. This gives 30 customers per circuit across three phases and 10 customers per circuit if the network is modelled on a single phase basis.

For the above-average length feeder, the transformer size is 400 kVA. The impedance of this transformer is also 4% on its own base. Information from Endeavour Energy indicates that a transformer of this size would be expected to supply 90 distinct customers. As stated, the network was modelled such that two circuits are connected to the transformer. This gives 45 loads across three phases per circuit or 15 loads on a single phase basis.

**5.6 Load Modelling**

Due to the random operating nature of loads connected to the LV network, a number of loading scenarios needed to be developed. These scenarios aid in understanding the potential impact of the domestic loads on low voltage feeder harmonic levels, however, they will never exactly match practical operating conditions. The modelling scenarios developed have been deliberately been tailored to represent a pessimistic view of network and loading operation and as such may represent the near to worst case scenario. This is justified as it is the worst case scenario which is of most importance to network operators for which they must design and operate their networks.

**5.6.1 Selection of Loads to be Modelled**

The complex nature of LV loading requires assumptions to be made with regard to the type and number of loads which will be operating simultaneously. To address this, the load models have been developed taking into account loads which have or are likely to have high penetration and are also of significant power rating. The loads that have been selected are not necessarily designed to reflect present loads which will likely be a mixture of older and more modern appliances, rather they have been specifically developed to represent modern appliances. Devices with low penetration or devices with very small power consumption (such as mobile phone chargers) have not been considered in the models. In addition, loads which are transient or are
turning on and off frequently such as refrigerators and microwave ovens have also been ignored. Based on these criteria, the load models are comprised of the following devices:

- LCD Televisions
- CRT Televisions
- DVD Players
- Personal Computers (PCs)
- PC Monitors
- Inverter Air Conditioners
- CFL Lighting

### 5.6.2 Load Modelling Methodology

The domestic, distorting loads are modelled as a combination of series of current sources connected in parallel to the LV network. Each current source represents the input current for each appliance or group of appliances based on the measurement results presented in Chapters 3 and 4. An example a load model is shown in Figure 5.2.

![Figure 5.2: Example of Load Model](image)

The magnitude and phase angle used in the current source for each appliance was defined using the magnitudes and phase angles for each appliance determined from the laboratory testing described in Chapters 3 and 4. Modelling the loads using both magnitude and phase angle accounts for the possibility of harmonic cancellation across the devices due to phase angle diversity.
One of the limitations of the load model is that only one type of each appliance (except for CFLs) has been characterised through laboratory testing. However, in [49], it was shown that phase angle diversity across the same device types, e.g. plasma televisions, made by different manufacturers is relatively low. Therefore, one device of each type may be considered to be relatively indicative of the performance of all devices of the same type. Consequently, the modelling methodology utilised here can be justified.

5.6.3 Load Magnitude Scenarios

Two scenarios were considered for non-linear loading magnitude. These have been defined as average and above average loading levels. The loading levels were determined by the number of appliances operating simultaneously. Based on data presented in [11] and [50], the composition of the two domestic loading scenarios is detailed in the following subsections based on appliance type.

5.6.3.1 Televisions

Data presented in [50] indicates that the average house has 1.9 televisions with an average age of eight years. According to [11] LCD televisions now account for more than 50% of sales and the average screen size is 73 cm. Given this data, the average domestic load model contains 2 televisions. One is a modern LCD television while the second is an older style 50 cm CRT television. The above-average domestic load model contains one additional LCD television.
5.6.3.2 DVD Players

Data in [11] puts DVD player penetration at 72%, that is 7 in every 10 residences have a DVD player. The average domestic load model contains one DVD player while the above-average domestic load model contains two.

5.6.3.3 Personal Computers (PC)

PC penetration is placed at 72% (7 in every 10 residences) by [50] and the average age is stated to be 3.5 years. The average domestic load model contains one PC, while the above-average domestic load model contains two PCs of the same type as the average model. In all cases, the PC has a monitor associated with it.

5.6.3.4 Air Conditioning

Air conditioner penetration is 60% (6 in every 10 residences) according to [11]. This is expected to increase to 80% by 2020. Of the air conditioners in service, 65% are claimed to be a non-ducted, reverse cycle type. Modern reverse cycle air conditioners marketed by the large manufacturers, now almost exclusively use inverter technology. There is little information available with regard to the average size of air conditioners in domestic residences, however, single phase reverse cycle inverter type air conditioners sizes appear to range between 3 kW and 10 kW.

The average domestic load model contains one modern 3.3 kW inverter air conditioner. The above-average domestic load consists of two 3.3 kW air conditioners.

5.6.3.5 Lighting

In all cases the CFLs, considered are 14/15 W CFLs which are replacements for 75 W incandescent globes. It is difficult to estimate the number of lights in use in a domestic premises at any one time, thus the scenarios developed were based on assumptions relating to domestic residence size and occupancy. The average load
contains six CFLs while the above average load contains 12 CFLs operating simultaneously.

The laboratory results presented in Chapter 3 showed that there is considerable variation in CFL performance across manufacturers. To address this variation and because special focus is placed on the impact of CFLs in this thesis, three CFL types are considered for each load, based on results obtained in Chapter 3. These three CFL types represent CFLs with the best harmonic performance, (lamp P), CFLs with average performance (lamp V) and poor performance (lamp C).

5.6.3.6 Summary of Load Composition

Based on the data given in the preceding subsections, the average load contains the following appliances:

- One CRT Television
- One LCD Television
- One DVD Player
- One 3.3 kW Inverter Air Conditioner
- One Personal Computer and Monitor
- Six 14/15 W CFLs

Figure 5.3 shows the harmonic currents injected by each of the above appliances based on an undistorted input voltage. The major harmonic loads are immediately obvious. These are the PC, inverter air conditioner and the CFLs, lamps C and V. The results seen for the air conditioner and PC are expected as these are the highest power devices included in the model. This figure indicates that although a single CFL is a low power load in terms of rated power, several, in this case six, CFLs can easily be the dominant source of harmonic current in a domestic premises depending on the type of lamp used. The effect of several CFLs operating together is apparent for higher order harmonics, especially in the case of Lamp C. This result clearly shows the importance of the CFL with respect to harmonic distortion and justifies the special attention which is being directed towards CFLs in this thesis.
The above-average load contains the following appliances:

- One CRT Television
- Two LCD Televisions
- Two DVD Players
- Two 3.3 kW Inverter Air Conditioners
- Two Personal Computers and Monitors
- Twelve 14/15 W CFLs

Figure 5.4 shows the harmonic currents injected by each of the above appliances based on an undistorted input voltage. Similar conclusions can be drawn here as were drawn from Figure 5.3. The CFLs, Lamps C and P, are clearly the dominant harmonic loads.
At any point in time, the electricity network is highly unlikely to be operating at undistorted nominal voltage. Voltage levels as well as background harmonic distortion levels will vary over time. Changes in the magnitudes of these parameters may impact on the current drawn by appliances connected to the network and this must be considered when models are developed, and used.

Chapters 2 and 3 examined the impact of changes in supply voltage magnitude on the electrical behaviour of equipment. Overall, analysis showed that the harmonic distortion of the supply voltage waveform had a much greater impact on equipment input current than changes in supply voltage magnitude. Modelling scenarios are therefore considered for changes in supply voltage waveform distortion while scenarios for changes in supply voltage magnitude are ignored. Three scenarios are considered; the undistorted case, the case for harmonic test waveform 1 as detailed in Section 3.2.2 and the case for harmonic test waveform 2 as detailed in Section 3.2.2
5.6.5 Overall Loading Levels

Based on the loading magnitude, network operating conditions and CFL scenarios described in Section 5.6.4, Figures 5.5 – 5.9 show the injected currents for the average load model scenario for 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 15\textsuperscript{th} and 21\textsuperscript{st} harmonic currents respectively. These figures clearly show the impact of the addition of CFLs to the load model under both undistorted and distorted input voltage conditions.

![3rd Harmonic (Average Load Scenario)](image)

**Figure 5.5: 3\textsuperscript{rd} Harmonic Input Currents for the Average Load Model**

![5th Harmonic (Average Load Scenario)](image)

**Figure 5.6: 5\textsuperscript{th} Harmonic Input Currents for the Average Load Model**
Figure 5.7: 7th Harmonic Input Currents for the Average Load Model

Figure 5.8: 15th Harmonic Input Currents for the Average Load Model
Figure 5.9: 21st Harmonic Input Currents for the Average Load Model

From examination of Figures 5.5 – 5.9 the following observations can be made:

- 3rd harmonic levels increase on the no CFL scenario when CFLs are added for all CFL types (lamps C, P and V). For each CFL scenario, the 3rd harmonic current decreases as the input voltage waveform overall distortion level (voltage THD) increases.
- 5th harmonic levels increase for the no CFL case for two out of three CFL types considered. Increasing the distortion level on the input voltage had inconsistent results. For harmonic test waveform 1, there was a significant reduction in the harmonic current for the no CFL, lamp C and lamp P cases. For harmonic test waveform 2 all current levels increased strongly on the undistorted input voltage case.
- For 7th harmonic current, the addition of CFLs leads to a decrease in the injected current for two out of the three CFL types considered. Application of harmonic test waveform 1 leads to decreases in current for all of the CFL scenarios considered compared to the undistorted input voltage case. Application of harmonic test waveform 2 leads to increases in current for all scenarios compared to the harmonic test waveform 1 case but had inconsistent impact based on the levels obtained when an undistorted input voltage was used.
- 15th harmonic current levels decreased for the no CFL case for two out of three CFLs types considered. In all cases, use of distorted input voltages lead to
currents less than those obtained when an undistorted input voltage was used. Of particular note are the strong reductions, compared to the undistorted input voltage case, observed for the no CFL and lamp P cases when harmonic test waveform 2 was used as the input voltage.

- With the exception of the lamp P scenario, addition of CFLs to the load model increased the 21\textsuperscript{st} harmonic current. In all but one case, use of distorted input voltages lead to increases in current compared to the case where an undistorted input voltage was used.

Figures 5.10 – 5.14 show the injected currents for the above-average load model scenario for 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 15\textsuperscript{th} and 21\textsuperscript{st} harmonic currents respectively. Figures 5.10 – 5.14 show similar characteristics to those observed in Figures 5.5 – 5.9, however, the magnitudes of the harmonic currents are larger since the above-average load model contains a larger number of harmonic current sources. The exception to this is the 5\textsuperscript{th} harmonic where the above average load models show a different distribution of harmonic currents. For the above-average load model, 5\textsuperscript{th} harmonic current levels for the undistorted input voltage waveform case are smaller in proportion to the 5\textsuperscript{th} harmonic currents for the harmonic test waveforms 1 and 2 cases than was observed for the average load model.
Figure 5.11: 5th Harmonic Input Currents for the Above Average Load Model

Figure 5.12: 7th Harmonic Input Currents for the Above Average Load Model
5.7 Comparison of Simulation Loading Levels with Field Measurements

In order to gain an understanding of how the simulated loading levels represent present domestic loading levels, the harmonic current data used to simulate the modern domestic load has been compared to harmonic current measurements taken at five domestic residences. The monitoring locations represent fairly typical domestic premises. Three of the monitored sites are family homes comprised of
adults and one or two children. The other two monitored sites are occupied by two adults.

It should be noted that a range of factors prevent strong comparison between simulated data and measured data. Factors limiting comparison between simulated and measured data include:

- The appliance mix at the monitored locations will not necessarily reflect the appliance composition in the simulated load.
- Simulated loading levels may not correlate well with the loading levels at the monitored sites. This is particularly the case for the extreme loading levels which is based on heavy harmonic loading levels.
- The simulation data is based on the load containing only modern appliances. The load at the monitored sites will include a range of older and modern appliances.

Given the limitations detailed above, comparisons made in this section are informative only. For each of the monitored sites, measured data is represented by three statistical measures; average, 95th percentile and maximum. For the simulated data, the data used for comparison with measured data is the loading level for the No CFL case. The use of the No CFL scenario for comparisons is justified as the monitored sites did not have CFLs installed at the time of measurement. The three simulated input voltage scenarios; undistorted, harmonic test waveform 1 and harmonic test waveform 2 are used in the comparison.

Figure 5.15 shows a comparison of measured data with simulated data for 3rd harmonic current. It can be seen that the simulated loading levels are within the measured current harmonic levels in all cases. In fact, in some cases, the measured loading levels are greater than the simulated loading levels. This may be due to the loads at some of the monitored site including older style appliances which have harmonic current performance which is worse than for the case of modern appliances as discussed in Chapter 4 (e.g. the case of CRT versus plasma and LCD televisions). Overall, the indication is that simulated loading levels will represent actual loading levels well.
Figure 5.15: Comparison of Measured Data with Simulated Data for 3rd Harmonic Current

Figures 5.16 - 5.19 show comparisons of measured data with simulated data for 5th harmonic, 7th harmonic, 15th harmonic and 21st harmonic respectively.

Figure 5.16: Comparison of Measured Data with Simulated Data for 5th Harmonic Current
Figure 5.17: Comparison of Measured Data with Simulated Data for 7th Harmonic Current

Figure 5.18: Comparison of Measured Data with Simulated Data for 15th Harmonic Current
5.8 Summary

This chapter has described the development of software models designed to assess the impact of the modern domestic load on low voltage distribution system harmonic levels. All facets of model design have been described. The distribution network is modelled as a series of impedances using data relevant to actual systems. Loads are modelled as harmonic current sources using the characteristic current values obtained from the laboratory testing performed on the appliances described in Chapters 3 and 4.

Collation of the laboratory measurements outlined in Chapters 3 and 4 into harmonic current injecting load models has revealed some interesting properties of the modern domestic load. The PC, inverter air conditioner and CFLs, depending on lamp type, are found to be the dominant injectors of harmonic currents. Overall, it has been found that six CFLs of a particular type can easily be the dominant harmonic load in a domestic residence in spite of the fact that the fundamental power rating of other
equipment, especially the air conditioner, is much higher than that of the CFLs. This justifies the special attention which is being dedicated to the CFL in this thesis.

Comparisons have been made between simulated loading levels and harmonic current levels measured at a number of domestic residences. Although there are various limitations which prevent rigorous comparison between measured and simulated data, overall, simulated data compares well with measured data.

For model implementation, a range of feeder length and loading scenarios have been adopted in an attempt to reflect the diversity of practical electricity networks. Each of these scenarios has been detailed and the rationale behind them described. Phase diversity between disparate harmonic sources has been addressed through use of current source models which include both current magnitude and phase angle values. The next chapter of this thesis will detail the results obtained using the models described in this chapter.
CHAPTER 6 : RESULTS OF SIMULATION WORK

6.1 Introduction

This chapter presents the results of the network simulation studies carried out using the models described in the previous chapter. These models have been developed to investigate the impact of the modern domestic load on low voltage distribution system harmonic voltage levels. Particular attention is paid to the impact of CFLs, a load which has recently had rapidly increasing penetration levels, which have harmonic profiles atypical of almost all other low voltage appliances.

Results are presented for all of the modelling scenarios which have been developed. The results presented have been grouped based on the input voltage scenarios described in Chapter 5. These scenarios correspond to load models based on results obtained when the appliances were supplied with (a) undistorted input voltage, (b) harmonic test waveform 1 and (c) harmonic test waveform 2. For all models, harmonic voltage levels are obtained at both the sending or distribution transformer end, and at the remote end of the low voltage feeder.

The results presented in this chapter only indicate the impact on harmonic voltage levels due to the modelled load. The influence of upstream harmonic levels propagating to the low voltage network has not been considered (as stated previously) and is not included in the models. In practice, harmonic voltage levels at any site will be due to a combination of the impact of the downstream load along with harmonics propagating from higher voltage levels. The harmonic levels obtained from the models will not necessarily reflect harmonic levels which would be measured in the field. However, this does not present itself as an issue due to the fact that the object of the study is to determine the specific contribution of the modern domestic load to harmonic levels. It was never the intention of the models to indicate overall harmonic levels, rather only those related to the domestic load.
6.1.1 Audio Frequency Load Control Signals

Many electricity distributors utilise audio frequency load control signalling to control loads such as off-peak hot water heating and street lighting. Two common injection frequencies used by Australian electricity distributors lie close to the 15th harmonic (750 Hz) and the 21st harmonic (1050 Hz).

An issue which has been identified with the wide-spread adoption of CFLs is the potential for interference with these injection signals [12]. Results of laboratory testing of CFLs presented in Chapter 3 showed that some CFLs will inject harmonic currents up to high harmonic orders including those near ripple injection frequencies. If these harmonic currents lead to high harmonic voltages this may cause problems with the operation of audio frequency ripple control relays affecting load control. In this chapter, special emphasis is placed on investigating the impact on ripple control signals for those models which include CFLs.

6.1.2 Harmonic Limits

Recommended planning levels for the harmonics of interest examined in this chapter from AS/NZS HB264 [51] are shown in Table 6.1. These planning levels are used as effective limits for harmonics by many Australian electricity distributors. Throughout this chapter, model results will be compared to these planning levels.

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Planning Level (% of 230V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd</td>
<td>4.5</td>
</tr>
<tr>
<td>5th</td>
<td>5.5</td>
</tr>
<tr>
<td>7th</td>
<td>4.5</td>
</tr>
<tr>
<td>15th</td>
<td>0.3</td>
</tr>
<tr>
<td>21st</td>
<td>0.2</td>
</tr>
</tbody>
</table>

6.2 Results of Models Based on Undistorted Input Voltages

The results presented in this section are established using the load models developed based on domestic appliance harmonic load currents which were measured when each appliance was supplied by a sinusoidal (undistorted) input voltage. These models represent the simplest scenario where distortion of the input voltage is not
considered. This is highly unlikely to be the case in practice due to the fact that input voltage at almost any point on the electricity network will have some level of distortion. However, the model is useful as a base case against which other modelled scenarios can be compared.

Figure 6.1 shows the harmonic voltages obtained at the sending (transformer) and remote end of the low voltage feeder for the average feeder length and average loading level scenario. Results are presented for the scenario without CFLs included and for each of the three CFL types modelled.

Examination of Figure 6.1 shows an immediate unusual distribution of harmonic orders for this basic model. It can be seen in these figures that 15\textsuperscript{th} harmonic and to a lesser extent 7\textsuperscript{th} harmonic levels are very high. 15\textsuperscript{th} harmonic is seen to be the dominant or second largest harmonic order for almost all of the CFL types modelled. This harmonic profile is not typical of what would currently be observed in the field.

Data in Chapter 5 shows that the 3\textsuperscript{rd} harmonic is the dominant current harmonic order injected by the load models followed by 7\textsuperscript{th}, 5\textsuperscript{th}, 15\textsuperscript{th} and 21\textsuperscript{st}. Thus it may be
expected that 3\textsuperscript{rd} harmonic will be dominant followed by 7\textsuperscript{th} and so on. However, since inductive reactance is directly proportional to the harmonic order, this simple assumption is invalid. 15\textsuperscript{th} harmonic levels are higher than 3\textsuperscript{rd} harmonic levels because the inductive reactance of the network at the 15\textsuperscript{th} harmonic is 5 times greater than that at the 3\textsuperscript{rd} harmonic while the injected 15\textsuperscript{th} harmonic current magnitude is not 5 times smaller than 3\textsuperscript{rd} harmonic current magnitudes. 7\textsuperscript{th} harmonic levels are as expected because this is the second largest harmonic component and interacts with a inductive reactance which is 7 times larger than that seen at fundamental frequency. It is unclear whether this unusual harmonic profile is due to the simplistic nature of this model (i.e. load models based on undistorted input voltages) or is the profile that can be expected if the network was loaded with modern appliances and upstream harmonic influences were not present.

Further analysis of Figure 6.1 shows that the local load modelled here is only producing modest levels of harmonic voltage at the sending end of the feeder. For the remote end of the feeder, it can be seen that in all cases, harmonics voltage levels are higher than at the sending end. Field monitoring conducted in relation to work presented in this thesis shows that this is the case in practice, indicating that the model is performing as expected. Although harmonic levels at the remote end are higher than those at the sending end they are still relatively low in most cases, with the exception of 15\textsuperscript{th} harmonic.

Table 6.2 shows the harmonic levels illustrated in Figure 6.1 for the basic load (no CFL scenario) (expressed as a percentage of 230 V):

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Sending End (% of 230 V)</th>
<th>Remote End (% of 230 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.47</td>
<td>2.27</td>
</tr>
<tr>
<td>5</td>
<td>0.35</td>
<td>0.67</td>
</tr>
<tr>
<td>7</td>
<td>0.75</td>
<td>1.43</td>
</tr>
<tr>
<td>15</td>
<td>0.51</td>
<td>2.37</td>
</tr>
<tr>
<td>21</td>
<td>0.07</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Comparing the values in Table 6.2 to the harmonic limits in Table 6.1, 3rd, 5th and 7th harmonic levels are well within limits. 15th harmonic levels are exceeding the limit at both the sending and remote ends of the feeder, while 21st harmonic levels are exceeding the limit at the remote end of the feeder.

Examination of the impact of including different types of CFLs in the model shows that the CFLs will have significant impact on harmonic levels. The results show that the model produces different harmonic voltages depending on the type of CFL included, with no two CFL types having the same impact. Table 6.3 shows the effect of adding each CFL type on each of the harmonic of interest. The data in this table is expressed as a percentage of the value obtained for the no CFL scenario, thus direct comparison can be made.

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>CFL</th>
<th>Sending End</th>
<th>Remote End</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3rd (% of no CFL Value)</td>
<td>5th (% of no CFL Value)</td>
<td>7th (% of no CFL Value)</td>
</tr>
<tr>
<td>Lamp C</td>
<td>131</td>
<td>115</td>
<td>82</td>
</tr>
<tr>
<td>Lamp P</td>
<td>106</td>
<td>115</td>
<td>103</td>
</tr>
<tr>
<td>Lamp V</td>
<td>152</td>
<td>66</td>
<td>88</td>
</tr>
<tr>
<td>Lamp C</td>
<td>132</td>
<td>116</td>
<td>82</td>
</tr>
<tr>
<td>Lamp P</td>
<td>105</td>
<td>116</td>
<td>103</td>
</tr>
<tr>
<td>Lamp V</td>
<td>154</td>
<td>66</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 6.3 shows that the addition of the CFLs to the load model has significant impact on harmonic levels; whether it be an increase or a decrease. The only consistent behaviour across all CFL types is an increase in 3rd harmonic voltage compared to the no CFL case. This is particularly strong for lamp V where levels are 1.5 times those observed for the no CFL scenario. Compared to the No CFL scenario, the following specific impacts can be stated for each CFL type:

- **Lamp C** – Lamp C is the CFL which had the highest harmonic content as detailed in Chapter 3. Addition of six of lamp C to the circuit results in increases
in all harmonic orders except for the 7th. A decrease in the 7th harmonic indicates that the 7th harmonic current due to the CFL is cancelling with some of the 7th harmonic current due to the other loads. The most significant impact of lamp C is a large increase in 21st harmonic levels, which is an increase of more than 2.5 times on the no CFL case when lamp C is added to the model.

- **Lamp P** – Addition of lamp P to the model results in increases in 3rd, 5th and 7th harmonic levels and decreases in 15th and 21st harmonic levels compared to the no CFL case. The most significant impact is a significant reduction in 21st harmonic levels with levels being approximately 70% of the no CFL scenario when lamp P is added to the model.

- **Lamp V** – The impact of lamp V is to increase 3rd and 21st harmonic levels and decrease all other harmonic levels compared to the no CFL case. The largest change is seen for 3rd harmonic with levels being 1.5 times that of the no CFL scenario.

The observation that the CFLs have the most significant impact on harmonic levels indicates the importance of this load. It further demonstrates that even though individually a small load, the impact on harmonic levels of many CFLs operating together cannot be ignored.

Figure 6.2 shows the result of the model for the scenario of average feeder length and above-average loading scenario. The results for this scenario are similar to those observed for the average loading model scenario. In general, the harmonic profiles are the same. However, harmonics levels are higher due to more distorting loads being connected. One of the major differences is 21st harmonic levels which increase significantly for this scenario particularly at the remote end of the feeder. This indicates that this loading scenario corresponds to a case where proportionally greater 21st harmonic current levels are presented compared to other harmonic current levels.
Figures 6.3 and 6.4 show the model results for the above-average feeder length/above average loading level and above-average feeder length/above-average loading level scenarios. Similar results are seen for these models as were observed in Figure 6.2. However, harmonic levels are generally higher since these two scenarios correspond to the highest numbers of distorting loads. Again, the same issues with 15th and 21st harmonic magnitude can be identified in the results from these models.

Based on Figure 6.4, harmonic levels have reached quite high levels and would exceed harmonic levels currently observed at most sites in the field tests based on monitoring. However, this model was designed to reflect a worst-case scenario. Given this scenario, it is clear that if the network is loaded to capacity and feeder lengths are long, harmonic currents due to modern appliances can easily cause harmonic voltage levels to exceed the planning limits shown in Table 6.1 at the remote end of low voltage feeders. Addition of CFLs to the network generally appear to exacerbate this problem.
The unusual harmonic profiles identified with the models based on values obtained using undistorted input voltages indicate that these models may be too simplistic. This is because undistorted input voltages are almost non-existent in practice. Results presented in Chapters 3 and 4 indicated that distortion of the input voltage can have
significant impact on the harmonic currents drawn by appliances. In order to better represent actual network operating conditions, further models have been constructed based on data obtained when appliances were supplied using distorted input voltages. The results of these models are discussed in Sections 6.3 and 6.4.

6.3 Results of Models Based on Harmonic Test Waveform 1

Figure 6.5 shows the result of the average feeder length/average load scenario model constructed using loading levels based on appliance characteristics when harmonic test waveform 1 as defined in Section 3.2.2 was used as the input voltage.

Comparison of Figure 6.5 to Figure 6.1, that are based on the same feeder length and loading scenario, show some immediate differences in the profile of harmonics levels. While still high, particularly compared to 5th harmonic levels, the 15th harmonic no longer stands out as being very high and has decreased for all modelled scenarios. 3rd harmonic levels are also seen to decrease for all scenarios while 21st harmonic levels have increased for all scenarios. Results are mixed for 5th and 7th harmonic. Of particular note is the profile of the 7th harmonic which is now the dominant or second largest harmonic component for all scenarios.
Once again, the local load is only producing quite small levels of harmonic voltage at the sending end of the feeder. Table 6.4 shows the harmonic voltage distortion levels at the sending and remote ends of the feeder for the basic load without any CFLs (presented as a percentage of 230 V).

**Table 6.4: Harmonic Levels for the Basic Load (no CFL scenario)**

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Sending End (% of 230 V)</th>
<th>Remote End (% of 230 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.35</td>
<td>1.66</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
<td>1.02</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>1.85</td>
</tr>
<tr>
<td>15</td>
<td>0.24</td>
<td>1.13</td>
</tr>
<tr>
<td>21</td>
<td>0.2</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The impact of adding CFLs to this model is shown in Table 6.5 where values are expressed as a percentage of the value obtained for the no CFL scenario.

**Table 6.5: Impact of Adding CFLs to Load Models – Harmonic Test Waveform 1 Input Voltage**

<table>
<thead>
<tr>
<th>CFL</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; (% of no CFL Value)</th>
<th>5&lt;sup&gt;th&lt;/sup&gt; (% of no CFL Value)</th>
<th>7&lt;sup&gt;th&lt;/sup&gt; (% of no CFL Value)</th>
<th>15&lt;sup&gt;th&lt;/sup&gt; (% of no CFL Value)</th>
<th>21&lt;sup&gt;st&lt;/sup&gt; (% of no CFL Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp C</td>
<td>130</td>
<td>112</td>
<td>102</td>
<td>132</td>
<td>152</td>
</tr>
<tr>
<td>Lamp P</td>
<td>105</td>
<td>86</td>
<td>85</td>
<td>100</td>
<td>130</td>
</tr>
<tr>
<td>Lamp V</td>
<td>121</td>
<td>154</td>
<td>144</td>
<td>166</td>
<td>89</td>
</tr>
<tr>
<td>Lamp C</td>
<td>131</td>
<td>112</td>
<td>103</td>
<td>131</td>
<td>152</td>
</tr>
<tr>
<td>Lamp P</td>
<td>105</td>
<td>86</td>
<td>84</td>
<td>99</td>
<td>131</td>
</tr>
<tr>
<td>Lamp V</td>
<td>122</td>
<td>156</td>
<td>144</td>
<td>166</td>
<td>90</td>
</tr>
</tbody>
</table>

The data shown in Table 6.5 can be summarised by the following:

- **Lamp C** – Addition of lamp C to the model results in increased harmonic voltage levels for all harmonic orders compared to the no CFL case. The highest increase is seen for the 21<sup>st</sup> harmonic with levels at 1.5 times the value obtained for the no
CFL case. These levels of 21st harmonic may be of concern with regard to load control ripple injection signals.

- **Lamp P** – Addition of lamp P to the model results in mixed changes to harmonic voltage levels. 3rd and 21st harmonic levels have increased, while 5th and 7th harmonic levels have decreased. For 15th harmonic, a slight increase is observed at the sending and of the feeder and a slight decrease is observed at the remote end. The maximum increase is seen for 21st harmonic with levels being 130% of the no CFL scenario. Similar levels of reduction are observed for 5th and 7th harmonic levels, with harmonic voltages falling to approximately 85% of the no CFL scenario voltages.

- **Lamp V** – Addition of lamp V to the model results in increases across all harmonic orders except the 21st. The strong increase is observed for 15th harmonic where levels are 166% of the no CFL scenario levels. 21st harmonic levels decrease to approximately 90% of no CFL levels.

Figures 6.6 - 6.8 show the model results for the other feeder length and loading scenarios considered. These scenarios are average feeder length/above-average load, above-average feeder length/average load and above-average feeder length/above-average load respectively.
Figure 6.6: Model Results for Harmonic Test Waveform 1 Input Voltage Average Feeder Length/Above-Average Loading Level Scenario

Figure 6.7: Model Results for Harmonic Test Waveform 1 Input Voltage Above-Average Feeder Length/Average Loading Level Scenario
Figures 6.6 – 6.8 show that the harmonic levels basically maintain the same profile. However, magnitudes increase as the amount of distorting load included in the model increases, which is effectively what is happening as feeder length or loading level is increased.

Maximum harmonic voltage levels are observed for the above average feeder length/above-average loading level scenario as shown in Figure 6.8. For this scenario, harmonic levels are quite large, especially at the end of the feeder. Under this scenario, the planning limits shown in Table 6.1 would be exceeded at the remote end of the feeder as follows:

- 3rd Harmonic : Under all modelled scenarios
- 5th Harmonic : For the scenario where lamp V is the CFL modelled
- 7th Harmonic : Under all modelled scenarios
- 15th Harmonic : Under all modelled scenarios
- 21st Harmonic : Under all modelled scenarios
15\textsuperscript{th} and 21\textsuperscript{st} harmonic levels would be of a sufficient magnitude to interfere with audio frequency ripple control signals whose injection frequencies are close to these harmonic orders.

6.4 Results of Models Based on Harmonic Test Waveform 2

Figure 6.9 shows the results of the model for the average feeder length/average loading scenario. For this model, the load values used correspond with those obtained when harmonic test waveform 2, as defined in Section 3.2.2, was used as the input voltage.

Comparing Figure 6.9 to Figures 6.1 and 6.5, which show the same feeder length and loading scenarios, it can be seen that the use of harmonic test waveform 2 as the input voltage results in a harmonic profile which is significantly different to those obtained for the undistorted input voltage (Figure 6.1) and the harmonic test waveform 1 (Figure 6.5) scenarios. Reductions in 3\textsuperscript{rd} and 15\textsuperscript{th} harmonic levels and increases in 5\textsuperscript{th} and 7\textsuperscript{th} harmonic levels are observed for all CFL scenarios. Comparisons of 21\textsuperscript{st} harmonic levels show variable results with increases for some CFL types and decreases for others.
Table 6.6 shows the harmonic voltage distortion levels at the sending and remote ends of the feeder for the basic load without any CFLs (presented as a percentage of 230 V).

Table 6.6: Harmonic Levels for the Basic Load (no CFL scenario)

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Sending End (% of 230 V)</th>
<th>Remote End (% of 230 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.20</td>
<td>0.98</td>
</tr>
<tr>
<td>5</td>
<td>0.60</td>
<td>2.80</td>
</tr>
<tr>
<td>7</td>
<td>0.57</td>
<td>2.69</td>
</tr>
<tr>
<td>15</td>
<td>0.10</td>
<td>0.43</td>
</tr>
<tr>
<td>21</td>
<td>0.26</td>
<td>1.21</td>
</tr>
</tbody>
</table>

The impact of adding CFLs to this model is shown in Table 6.7 where values are again expressed as percentages of the value obtained for the no CFL scenario.

Table 6.7: Impact of Adding CFLs to Load Models – Harmonic Test Waveform 2 Input Voltage

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>CFL</th>
<th>Sending End</th>
<th>Remote End</th>
</tr>
</thead>
<tbody>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; (% of no CFL Value)</td>
<td>Lamp C</td>
<td>136</td>
<td>117</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; (% of no CFL Value)</td>
<td>Lamp C</td>
<td>102</td>
<td>100</td>
</tr>
<tr>
<td>7&lt;sup&gt;th&lt;/sup&gt; (% of no CFL Value)</td>
<td>Lamp C</td>
<td>123</td>
<td>130</td>
</tr>
<tr>
<td>15&lt;sup&gt;th&lt;/sup&gt; (% of no CFL Value)</td>
<td>Lamp C</td>
<td>135</td>
<td>116</td>
</tr>
<tr>
<td>21&lt;sup&gt;st&lt;/sup&gt; (% of no CFL Value)</td>
<td>Lamp C</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td>21&lt;sup&gt;st&lt;/sup&gt; (% of no CFL Value)</td>
<td>Lamp V</td>
<td>124</td>
<td>130</td>
</tr>
</tbody>
</table>

Table 6.7 shows that addition of CFLs will result in increases or no change in 3<sup>rd</sup>, 5<sup>th</sup> and 7<sup>th</sup> harmonic levels at both the sending and remote ends of the feeder for all of the CFL types modelled. For the other harmonic orders, the impact of each CFL on the base case is as follows:
• **Lamp C** – Addition of lamp C to the model results in very large increases in 15\textsuperscript{th} and 21\textsuperscript{st} harmonic levels at both the sending and remote end of the feeder. For 15\textsuperscript{th} harmonic the voltage is 0.82 V at the sending end and 3.79 V at the remote end. For 21\textsuperscript{st} harmonic, the harmonic voltage is 1.3 V at the sending end and 5.99 V at the remote end. These voltage levels would definitely interfere with ripple injection signals.

• **Lamp P** – Addition of lamp P to the model results in reductions in 15\textsuperscript{th} and 21\textsuperscript{st} harmonic levels compared to the no CFL scenario.

• **Lamp V** – Addition of lamp V to the model results in a significant increase in 15\textsuperscript{th} harmonic levels at both the sending and remote end of the feeder. For 21\textsuperscript{st} harmonic, addition of lamp V results in a very large decrease in 21\textsuperscript{st} harmonic levels indicating that the harmonic currents injected by lamp P are cancelling 21\textsuperscript{st} harmonic currents due to the other loads.

For the remaining feeder length and loading level scenarios, similar effects are seen as those observed for the cases where undistorted and Harmonic Test Waveform 1 voltages were used as the input. Overall, harmonic profiles generally remain similar, however, the magnitude of the harmonic voltages changes as more distorting load is added to the model. Figures 6.10, 6.11 and 6.12 show the results of the average feeder length/above-average load scenarios, above-average feeder length/average load scenario and above-average feeder length/above-average load scenario respectively.
Figure 6.10: Model Results for Harmonic Test Waveform 2 Input Voltage Average Feeder Length/Above-Average Loading Level Scenario

Figure 6.11: Model Results for Harmonic Test Waveform 2 Input Voltage Above-Average Feeder Length/ Average Loading Level Scenario
Once again, maximum harmonic voltage levels are observed for the above average feeder length/above-average loading level scenario shown in Figure 6.12. For this scenario, harmonic levels are quite large especially at the end of the feeder. Under this scenario, the planning limits shown in Table 6.1 would be exceeded at the remote end of the feeder under all modelled scenarios.

15th and 21st harmonic levels may be of sufficient magnitude to interfere with audio frequency ripple control signals whose injection frequency is close to these harmonic orders.

6.5 Summary

This chapter presented the results obtained using models developed to investigate the impact of the modern domestic load on low voltage distribution system harmonic voltage levels. Particular attention has been made regarding the impact of CFLs on harmonic levels. CFLs are a load which has recently experienced a very rapid increase in penetration levels. These devices have been shown to have harmonic spectra atypical to that of other domestic appliances. In some cases, this includes significant levels of harmonic current at high harmonic orders. Overall, based on the
assumptions detailed in the previous chapter, the modelling exercise has been effective in estimating the impact of the modern domestic load on low voltage feeder harmonic voltage levels.

Three basic scenarios for implementing the magnitudes of the harmonic currents injected by each load have been considered. These are magnitudes corresponding to values measured when the appliances were supplied with undistorted voltage and when the appliances were supplied with 2 different distorted input voltages.

Overall, the majority of model results are reflective of credible harmonic magnitudes and profiles. The results most typical of harmonic profiles observed in the field were obtained by using models where the injected current levels were based on measurements of appliance behaviour when supplied with distorted input voltages as opposed to sinusoidal input voltages. This was expected since undistorted input voltages are very unlikely to be seen in practice. The results indicate that high to very high penetration of modern domestic appliances will result in harmonic voltage levels on low voltage feeders that will exceed Australian harmonic voltage planning levels.

The models also indicate that the profile of the harmonic voltages due to modern domestic appliances may not be the same as the traditional profile where low order harmonics dominate. There is evidence that if penetration of modern loads reaches very high levels, the dominant voltage harmonic due to interaction of local load current with network impedance may be the 7th or 15th harmonic.

For all models, it should be noted that the harmonic voltages obtained from the modelling is only the component of harmonic voltage due to local load. The influence of upstream harmonics will have a significant impact on the net harmonic levels seen in practice. Comparisons between the levels of harmonic voltage and field measurements conducted for this thesis indicate that the upstream load has a significant impact on non-triplen harmonic voltage levels. When this upstream impact is taken into account it is possible that harmonic profiles similar to those currently observed in the field will continue to be similar to those observed presently.
Special emphasis has been placed on the impact of CFLs on harmonic levels in this chapter. Results of modelling clearly show that a significant number of CFLs can have an impact on voltage harmonic levels. Compared to the case where no CFLs were included in load models, the following can be said of CFLs:

- The models indicate that the addition of CFLs to the load will result in increased 3rd harmonic voltage levels regardless of the type of CFL used. Depending on the distortion level of the input voltage, indications are that levels may be up to 1.5 times the values obtained for the scenario without CFLs. This result is expected given the fact that the phase angles of 3rd harmonic currents for the appliances tested in Chapters 3 and 4 tended to be similar.

- The impact of the CFLs on 5th and 7th harmonic levels was dependant on the CFL type and the input voltage scenario. There was no consistent behaviour observed across all scenarios with some scenarios leading to increases in harmonic voltages while others lead to decreases. Regardless of whether an increase or decrease was observed, the impact of CFLs on 5th and 7th harmonic levels was not as significant as that observed for 3rd harmonic levels. Given the variation in results, it seems likely that the impact of CFLs on 5th and 7th harmonic levels may be minimal and would likely be difficult to identify in any case.

- Depending on the input voltage scenario, very large increases in 15th and 21st harmonic voltage levels may be observed if the penetration of some types of CFLs is high. There is concern in the electricity supply industry that these high harmonic voltages at frequencies close to those used for audio frequency ripple injection load control signals may interfere with the operation of these load control systems. The results of the modelling undertaken in this thesis show that these concerns may have merit.
CHAPTER 7: COMPARISON BETWEEN SIMULATION RESULTS AND FIELD MEASUREMENT DATA

7.1 Introduction

This chapter compares the results of the simulation models with data measured at a number of sites in the field. It should be noted that it is impossible to directly compare the results of the simulation models with field measurements. Although the models are based on typical networks, it is impossible to locate a site to monitor which will have the same characteristics as the models. Instead, the comparisons presented here are designed to provide indication of whether model inputs (current harmonic levels) are within the realms of possibility.

7.2 Factors Affecting Comparisons between Model Results and Field Data

The following are factors which must be taken into account when assessing model results against measured data and explain why model results do not necessarily reflect practical outcomes:

1. Models are designed to represent worst case scenarios – The models were developed to simulate fully loaded circuits containing high levels of distorting load. In practice, few circuits are fully loaded and therefore measured harmonic levels are likely to be lower than those obtained using the models.

2. Upstream influences are ignored – In all cases, models were developed for the low voltage network only. As a result, the harmonic voltage levels measured are only those produced by the local load. The impact of upstream harmonics propagating into the low voltage network has been ignored. This is of particular importance for harmonics measured at the sending end of the feeder where the influence of upstream harmonics will be greatest. This is not a major issue for triplen harmonics since values of these will be low in the medium voltage network but will have a large impact on 5th and 7th harmonic values.
3. **Accurate modelling of loads is impossible** – It is not practical to accurately model every load connected to a low voltage feeder. The load models developed in this thesis represent loads with either high penetration levels or high power ratings. In addition, time diversity across appliances has been ignored. These factors limit the accuracy of the load models.

4. **For each CFL scenario the same CFL is used throughout the circuit** – When scenarios using CFLs were developed only a single type of CFL was added to the model for each scenario. This strategy was adopted in order to present a worst (or best) case scenario. In practice, CFLs of many different types will be operating simultaneously.

5. **Feeder conductor is homogenous** – The models have been developed using the same type of conductor for the whole length of the feeder. This is often not the case in practice.

6. **Accuracy of measurement at high harmonic orders is questionable** – The accuracy of measuring instrumentation both in the laboratory and in the field for high harmonic orders such as the 15th and 21st is questionable thus leading to unavoidable inaccuracies for these harmonic orders. This is particularly true for field measurements where older style monitoring instrumentation has been used. This instrumentation is not compliant with modern power quality monitoring standards and as such does not have the accuracy of modern instrumentation.

7. **Models comprise modern appliances only** – The load models which have been developed are comprised exclusively of modern appliances. In practice, it is unlikely that any load will be comprised solely of modern equipment. Instead, the load will contain a mix of old and new appliances.

### 7.3 Details of Measured Sites

Data from a numbers of sites in the field is available for comparison with the results of the simulation models. Although the models which have been developed are representative of typical low voltage networks on the Endeavour Energy electricity
network, it is difficult to identify sites which have the exact characteristics of each
modelled scenario. The sites which have been monitored do not have characteristics
identical to the modelled scenarios but have been selected to have similar
characteristics. The data utilised in this chapter is gathered from a number of sources
including some sites which have been specifically monitored for the purposes of the
work undertaken in this thesis.

7.4 Data Analysis

Each site included in this section was monitored for at least one week. The
simulation models have been developed to mimic loading behaviour during the
evening. If field data is to be compared to model results it is necessary to reduce the
measured field data so that the data analysed is only that corresponding to the same
time window of the day. This has been achieved by filtering the measured field data
such that only data corresponding to the time period 7pm – 11pm is retained. As the
simulation models are designed to represent peak loading levels, where highest
harmonic values are expected to occur, the 95th percentile value of the data obtained
during the assessed time period is taken to characterise the performance of each site.

7.5 Sites at Sending End of Low Voltage Feeder

Data was available from total of 19 sites at the sending end of low voltage feeders.
Transformer size and loading for each of these sites is shown in Table 7.1.
Table 7.1: Details for Sites at Sending End of Low Voltage Feeder

<table>
<thead>
<tr>
<th>Site</th>
<th>Transformer Rating (kVA)</th>
<th>Maximum Demand (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>315</td>
<td>Not Available</td>
</tr>
<tr>
<td>Site 2</td>
<td>500</td>
<td>Not Available</td>
</tr>
<tr>
<td>Site 3</td>
<td>500</td>
<td>Not Available</td>
</tr>
<tr>
<td>Site 4</td>
<td>500</td>
<td>Not Available</td>
</tr>
<tr>
<td>Site 5</td>
<td>315</td>
<td>75</td>
</tr>
<tr>
<td>Site 6</td>
<td>500</td>
<td>276</td>
</tr>
<tr>
<td>Site 7</td>
<td>500</td>
<td>360</td>
</tr>
<tr>
<td>Site 8</td>
<td>300</td>
<td>267</td>
</tr>
<tr>
<td>Site 9</td>
<td>500</td>
<td>256</td>
</tr>
<tr>
<td>Site 10</td>
<td>750</td>
<td>235</td>
</tr>
<tr>
<td>Site 11</td>
<td>300</td>
<td>240</td>
</tr>
<tr>
<td>Site 12</td>
<td>100</td>
<td>66</td>
</tr>
<tr>
<td>Site 13</td>
<td>315</td>
<td>231</td>
</tr>
<tr>
<td>Site 14</td>
<td>200</td>
<td>195</td>
</tr>
<tr>
<td>Site 15</td>
<td>200</td>
<td>92</td>
</tr>
<tr>
<td>Site 16</td>
<td>200</td>
<td>115</td>
</tr>
<tr>
<td>Site 17</td>
<td>250</td>
<td>209</td>
</tr>
<tr>
<td>Site 18</td>
<td>250</td>
<td>175</td>
</tr>
<tr>
<td>Site 19</td>
<td>250</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

Table 7.1 shows that transformer size ranges between 100 kVA and 500 kVA with some transformers heavily load (e.g. Site 8) and others lightly loaded (e.g. Site 5).

Table 7.2 shows the 95th percentile harmonic voltage levels recorded at each site. The minimum and maximum values are also shown and it is these values which will be used for further analysis.
Table 7.2: 95th Percentile Harmonic Voltages Recorded at Each Site

<table>
<thead>
<tr>
<th>Site</th>
<th>3rd Harmonic (% of 230V)</th>
<th>5th Harmonic (% of 230V)</th>
<th>7th Harmonic (% of 230V)</th>
<th>15th Harmonic (% of 230V)</th>
<th>21st Harmonic (% of 230V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>0.35</td>
<td>3.22</td>
<td>0.72</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Site 2</td>
<td>0.44</td>
<td>1.08</td>
<td>0.45</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Site 3</td>
<td>0.60</td>
<td>3.97</td>
<td>0.16</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>Site 4</td>
<td>0.15</td>
<td>2.66</td>
<td>0.83</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Site 5</td>
<td>0.69</td>
<td>3.62</td>
<td>0.92</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Site 6</td>
<td>0.71</td>
<td>2.67</td>
<td>0.48</td>
<td>0.13</td>
<td>N/A^1</td>
</tr>
<tr>
<td>Site 7</td>
<td>0.79</td>
<td>2.60</td>
<td>0.50</td>
<td>0.12</td>
<td>N/A^1</td>
</tr>
<tr>
<td>Site 8</td>
<td>0.77</td>
<td>2.63</td>
<td>0.48</td>
<td>0.12</td>
<td>N/A^1</td>
</tr>
<tr>
<td>Site 9</td>
<td>0.69</td>
<td>2.64</td>
<td>0.43</td>
<td>0.11</td>
<td>N/A^1</td>
</tr>
<tr>
<td>Site 10</td>
<td>1.20</td>
<td>3.42</td>
<td>1.23</td>
<td>0.20</td>
<td>N/A^1</td>
</tr>
<tr>
<td>Site 11</td>
<td>0.71</td>
<td>2.70</td>
<td>0.53</td>
<td>0.14</td>
<td>N/A^1</td>
</tr>
<tr>
<td>Site 12</td>
<td>0.20</td>
<td>2.58</td>
<td>1.40</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>Site 13</td>
<td>0.34</td>
<td>2.79</td>
<td>1.65</td>
<td>0.21</td>
<td>0.09</td>
</tr>
<tr>
<td>Site 14</td>
<td>0.75</td>
<td>2.82</td>
<td>1.49</td>
<td>0.39</td>
<td>0.15</td>
</tr>
<tr>
<td>Site 15</td>
<td>0.27</td>
<td>2.36</td>
<td>1.51</td>
<td>0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>Site 16</td>
<td>0.52</td>
<td>1.14</td>
<td>1.04</td>
<td>0.43</td>
<td>0.23</td>
</tr>
<tr>
<td>Site 17</td>
<td>0.87</td>
<td>2.96</td>
<td>0.85</td>
<td>0.60</td>
<td>0.00</td>
</tr>
<tr>
<td>Site 18</td>
<td>0.72</td>
<td>2.80</td>
<td>0.83</td>
<td>0.89</td>
<td>0.09</td>
</tr>
<tr>
<td>Site 19</td>
<td>0.45</td>
<td>3.04</td>
<td>1.03</td>
<td>0.23</td>
<td>0.07</td>
</tr>
</tbody>
</table>

| Minimum | 0.15 | 1.08 | 0.16 | 0.00 | 0.00 |
| Maximum | 1.20 | 3.97 | 1.65 | 0.89 | 0.23 |

^1 21st harmonic data was not able to be used from sites 6 – 11 because audio frequency injection control signals at these sites impact on 21st harmonic levels.

7.6 Sites at Remote End of Low Voltage Feeders

Data was available from a total of 8 sites at the remote ends of low voltage feeders. Table 7.3 shows the details for these sites.
Table 7.3: Details for Sites at Remote End of Low Voltage Feeder

<table>
<thead>
<tr>
<th>Site</th>
<th>Transformer Rating (kVA)</th>
<th>Maximum Demand (kVA)</th>
<th>Distance from Sending End (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>315</td>
<td>Not Available</td>
<td>210</td>
</tr>
<tr>
<td>Site 2</td>
<td>500</td>
<td>Not Available</td>
<td>293</td>
</tr>
<tr>
<td>Site 3</td>
<td>500</td>
<td>Not Available</td>
<td>140</td>
</tr>
<tr>
<td>Site 4</td>
<td>500</td>
<td>Not Available</td>
<td>380</td>
</tr>
<tr>
<td>Site 5</td>
<td>315</td>
<td>300</td>
<td>207</td>
</tr>
<tr>
<td>Site 6</td>
<td>315</td>
<td>75</td>
<td>282</td>
</tr>
<tr>
<td>Site 7</td>
<td>250</td>
<td>209</td>
<td>400</td>
</tr>
<tr>
<td>Site 8</td>
<td>250</td>
<td>Not Available</td>
<td>258</td>
</tr>
</tbody>
</table>

Table 7.4 shows the 95th percentile harmonic voltage levels recorded at each site. The minimum and maximum values are also shown and it is these values which will be used for further analysis.

Table 7.4: 95th Percentile Harmonic Voltages Recorded at Each Site

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>0.54</td>
<td>3.42</td>
<td>0.76</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>Site 2</td>
<td>1.74</td>
<td>1.36</td>
<td>0.72</td>
<td>0.33</td>
<td>0.15</td>
</tr>
<tr>
<td>Site 3</td>
<td>3.84</td>
<td>0.67</td>
<td>0.30</td>
<td>0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>Site 4</td>
<td>2.57</td>
<td>3.52</td>
<td>1.60</td>
<td>0.78</td>
<td>0.24</td>
</tr>
<tr>
<td>Site 5</td>
<td>0.91</td>
<td>3.25</td>
<td>0.84</td>
<td>0.31</td>
<td>0.14</td>
</tr>
<tr>
<td>Site 6</td>
<td>1.61</td>
<td>4.02</td>
<td>1.17</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td>Site 7</td>
<td>2.90</td>
<td>3.58</td>
<td>1.12</td>
<td>0.78</td>
<td>0.28</td>
</tr>
<tr>
<td>Site 8</td>
<td>0.86</td>
<td>3.04</td>
<td>1.03</td>
<td>0.38</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Minimum   | 0.54  | 0.67  | 0.30  | 0.05  | 0.00  |
Maximum   | 3.84  | 4.02  | 1.60  | 0.78  | 0.34  |

7.7 Comparisons

This section shows comparisons between model results and field measured data. Comparisons are made for each harmonic order of interest for both the sending and remote ends of the LV feeder. Comparisons have been made for each of the feeder
lengths and loading scenarios described in Chapters 5 and 6. For ease of visualisation, these scenarios have been abbreviated in all figures. The key to the abbreviations is as follows:

- The average feeder length/average loading levels scenario is abbreviated to AL/ALd
- The average feeder length/above-average loading levels scenario is abbreviated to AL/AALd
- The above-average feeder length/average loading levels scenario is abbreviated to AAL/ALd
- The above-average feeder length/above-average loading levels scenario is abbreviated to AAL/AALd

For all comparisons, the minimum and maximum field measured values are shown on each graph and are used as the comparison against the model results.

7.7.1 3rd Harmonic

Direct comparisons may be made between model results and field measurements for 3\textsuperscript{rd} harmonic at both the sending and remote ends of the LV feeder since almost all of the 3\textsuperscript{rd} (and all triplen) harmonic voltage seen on the LV circuit will be due to the local load. This is a result of the star-delta distribution transformers used in Australia which prevents most of the triplen harmonics from propagating upstream. Consequently, triplen harmonic levels in medium voltage systems are generally small resulting in little impact on triplen harmonic levels on other LV circuits.

7.7.1.1 Sending End of Feeder

Figure 7.1 shows the comparison between model results and field measured data for the sending end of the LV feeder for models based on undistorted input voltage. Figure 7.2 shows the same information for models based on harmonic test waveform 1 input voltage, while Figure 7.3 shows the same information for models based on harmonic test waveform 2 input voltage.
Figure 7.1: Comparison of Model Result with Field data for Sending End of Feeder for 3rd Harmonic – Undistorted Input Voltage

Figure 7.2: Comparison of Model Result with Field data for Sending End of Feeder for 3rd Harmonic – Harmonic Test Waveform 1 Input Voltage
Figures 7.1 – 7.3 show that the model results fall within the boundaries defined by the field measured data for all modelled scenarios except for the extreme feeder length/above-average loading scenario for the undistorted input voltage model.

### 7.7.1.2 Remote End of Feeder

Figure 7.4 shows the comparison between model results and field measured data for the remote end of the LV feeder for models based on undistorted input voltage. Figure 7.5 shows the same information for models based on harmonic test waveform 1 input voltage, while Figure 7.6 shows the same information for models based on harmonic test waveform 2 input voltage.

Figures 7.4 – 7.6 show that the models based on undistorted input voltages led to 3rd harmonic levels higher than those observed in the field. However, there is acceptable correlation between field measurements and model results for models based on the two harmonic test waveform input voltages.
Figure 7.4: Comparison of Model Result with Field data for Remote End of Feeder for 3rd Harmonic – Undistorted Input Voltage

Figure 7.5: Comparison of Model Result with Field data for Remote End of Feeder for 3rd Harmonic – Harmonic Test Waveform 1 Input Voltage
7.7.2 5th Harmonic

7.7.2.1 Sending End of Feeder

Direct comparison between model results and field data for non-triplen harmonics at the sending end of LV feeders is impossible since the model only examines harmonic voltages due to local loads. Field measurements will include harmonics due to local load along with significant harmonic voltages propagating from upstream sources. Consequently, direct comparisons between model results and field data cannot be made. The interaction between harmonic currents and LV feeder impedance along the feeder results in the influence of upstream harmonic voltages being much more apparent at the sending end of the feeder than at the remote end.

Figures 7.7 - 7.9 show comparisons between field data and model results for the models based on undistorted input voltage, harmonic test waveform 1 input voltage and harmonic test waveform 2 input voltage respectively. As expected, there is poor correlation between model results and field measured data, with the model results being much lower than the field measurements.
Figure 7.7: Comparison of Model Result with Field data for Sending End of Feeder for 5th Harmonic – Undistorted Input Voltage

Figure 7.8: Comparison of Model Result with Field data for Sending End of Feeder for 5th Harmonic – Harmonic Test Waveform 1 Input Voltage
7.7.2.2 Remote end of Feeder

Comparisons between model results and measured data for non-triplen harmonics are more relevant at the remote ends of feeders since the harmonic voltages present in these locations are predominately due to local load currents flowing through the relatively large impedance of the LV feeder. Upstream influences are not as significant at the remote end of the feeder as at the sending end.

Figure 7.10 shows the comparison between model result and field measured data for the remote end of the LV feeder for models based on undistorted input voltage. Figure 7.11 shows the same information for models based on harmonic test waveform 1 input voltage, while Figure 7.12 shows the same information for models based on harmonic test waveform 2 input voltage.
Figure 7.10: Comparison of Model Result with Field data for Remote End of Feeder for 5th Harmonic – Undistorted Input Voltage

Figure 7.11: Comparison of Model Result with Field data for Remote End of Feeder for 5th Harmonic – Harmonic Test Waveform 1 Input Voltage
Figures 7.10 – 7.12 show a much better correlation between model results and field measurements than was observed for the comparisons made at the sending end of the feeder.

7.7.3 7th Harmonic

7.7.3.1 Sending End of Feeder

Figures 7.13 - 7.15 show comparisons between model results and field measurements for the three input voltage scenarios considered; undistorted input voltage, harmonic test waveform 1 and harmonic test waveform 2. The figures show that that model results generally fall within the range of measured data. However, as was the case for 5th harmonic measurements, 7th harmonic levels at the sending end of the feeder will be highly influenced by upstream harmonics and as such, no conclusions with regard to comparisons between model results and field measurements can be made here with any degree of confidence.
Figure 7.13: Comparison of Model Result with Field data for Sending End of Feeder for 7th Harmonic – Undistorted Input Voltage

Figure 7.14: Comparison of Model Result with Field data for Sending End of Feeder for 7th Harmonic – Harmonic Test Waveform 1 Input Voltage
7.7.3.2 Remote end of Feeder

Figure 7.16 shows the comparison between model results and field measured data for the remote end of the LV feeder for models based on undistorted input voltage. Figure 7.17 shows the same information for models based on harmonic test waveform 1 input voltage, while Figure 7.18 shows the same information for models based on harmonic test waveform 2 input voltage.
The results presented in Figures 7.16 – 7.18 show that the results of modelling for 7th harmonic are considerably higher than levels measured in the field. The reasons for this discrepancy are related to the magnitude of the 7th harmonic current injected into the distribution system model as well as the network impedances. In Chapter 5, 7th harmonic was identified as the dominant harmonic current for the load models of the modern domestic appliances that have been utilised. This dominance does not come about because the devices have particularly large 7th harmonic currents, but rather cancellation effects mitigate the magnitude of lower order harmonics. The fact that the 7th harmonic was the dominant order injected lead to 7th harmonic also being the
dominant voltage harmonic for many of the model results presented in Chapter 6. For higher order harmonics, network impedance and length also plays an important role as impedance is directly proportional to the harmonic order. Even small currents can lead to large voltages at high harmonic orders. Therefore, there is a considerably higher margin for error as the harmonic order increases.

In practice it is questionable whether or not the 7\textsuperscript{th} harmonic will be the dominant harmonic load current and in turn it is questionable as to whether or not the 7\textsuperscript{th} harmonic should be the dominant voltage harmonic. However, these are the results which have been obtained based on the modelling scenarios that have been developed and they represent one possible outcome if field loading scenarios were to match those assumed in the modelling process.

7.7.4 15th Harmonic

7.7.4.1 Sending End of Feeder

Comparisons between field measurements and model results for 15\textsuperscript{th} harmonic levels at the sending end of the feeder are presented in Figures 7.19 – 7.21. Figure 7.19 presents comparisons for the models based on undistorted input voltages while Figures 7.20 and 7.21 present comparisons for models based on harmonic test waveform 1 and harmonic test waveform 2 input voltages respectively. It can be seen that the model results are within the range of values observed in the field for the majority of modelled scenarios.
Figure 7.19: Comparison of Model Result with Field data for Sending End of Feeder for 15th Harmonic – Undistorted Input Voltage

Figure 7.20: Comparison of Model Result with Field data for Sending End of Feeder for 15th Harmonic – Harmonic Test Waveform 1 Input Voltage
7.7.4.2 Remote end of Feeder

Figures 7.22 - 7.24 show comparisons between model results and field data for 15th harmonic levels at the remote end of the feeder for the models based on undistorted input voltage, harmonic test waveform 1 input voltage and harmonic test waveform 2 input voltage respectively.
Figures 7.23 – 7.24 show that the models tend to produce 15\textsuperscript{th} harmonic levels which are larger than those observed in the field. The closest correlation between field measurements and model results is achieved for models based on the harmonic test waveform 2 input voltage. The discrepancies between field measurements and model results for 15\textsuperscript{th} harmonic occur for similar reasons as the discrepancies observed for 7\textsuperscript{th} harmonic at the remote end of the feeder. At this harmonic order, small currents will lead to large voltages and any inaccuracies in the injected currents will lead to much larger inaccuracies in the measured voltage. It is clear that the load models developed are injecting higher 15\textsuperscript{th} harmonic currents than are observed in the field.
However, this may be the normal behaviour of modern loads, and 15th harmonic levels similar to those shown may be observed as more and more loads on the network are modernised.

7.7.5 21st Harmonic

7.7.5.1 Sending End of Feeder

Figures 7.25 - 7.27 show comparisons between model results and field measurements for 21st harmonic levels at the sending end of the feeder for the three input voltage scenarios considered; undistorted input voltage, harmonic test waveform 1 and harmonic test waveform 2. The figures show that the correlation between model results is strongly influenced by the modelled scenario. In general, scenarios based on extreme loading levels generally produce 21st harmonic levels considerably larger than the range of values observed in the field. In addition, scenarios involving lamp C which has a relatively large 21st harmonic component produce results larger than those seen in the field regardless of the input voltage upon which the model is based. Overall, best correlation between model results and field measurement is achieved for the models based on the harmonic test waveform 2 input voltage. Models based on this input voltage also showed the least variation in values for the different loading scenarios considered.

Figure 7.25: Comparison of Model Result with Field data for Sending End of Feeder for 21st Harmonic – Undistorted Input Voltage
Figure 7.26: Comparison of Model Result with Field data for Sending End of Feeder for 21st Harmonic – Harmonic Test Waveform 1 Input Voltage

Figure 7.27: Comparison of Model Result with Field data for Sending End of Feeder for 21st Harmonic – Harmonic Test Waveform 2 Input Voltage

7.7.5.2 Remote end of Feeder

Figure 7.28 shows the comparison between model results and field measured data for the remote end of the LV feeder for models based on undistorted input voltage. Figure 7.29 shows the same information for models based on harmonic test waveform 1 input voltage, while Figure 7.30 shows the same information for models based on harmonic test waveform 2 input voltage.

It can be seen that the model results are higher and in some cases, much higher than measured 21st harmonic levels for all modelled scenarios. Closest correlation
between field measurements and model results is achieved for the model based on values obtained using harmonic test waveform 2 input voltage. This lack of correlation is for the same reasons as were outlined (in Section 7.7.4) for the lack of correlation in 15\textsuperscript{th} harmonic values.

**Figure 7.28:** Comparison of Model Result with Field data for Remote End of Feeder for 21\textsuperscript{st} Harmonic – Undistorted Input Voltage

**Figure 7.29:** Comparison of Model Result with Field data for Remote End of Feeder for 21\textsuperscript{st} Harmonic – Harmonic Test Waveform 1 Input Voltage

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This chapter has compared the results of the models described in Chapters 5 and 6 with measured data from a number of sites in the field. There are a numbers of reasons that make direct comparison of model results with field data very difficult and these have been described. Notwithstanding these difficulties good correlation between field measurements and model results has been achieved for 3rd and 5th harmonic. Correlation between model results for the higher order harmonics examined; 7th, 15th and 21st, is not as strong and reasons for these discrepancies have been discussed. In all cases it is important to note that the models which have been developed represent a subset of scenarios which will never be exactly replicated in the field.

Figure 7.30: Comparison of Model Result with Field data for Remote End of Feeder for 21st Harmonic – Harmonic Test Waveform 2 Input Voltage

7.8 Summary
CHAPTER 8 : CONCLUSIONS

8.1 Conclusions based on Research

This thesis investigated the electrical performance of a range of modern domestic appliances and their potential impact on low voltage distribution network power quality levels; specifically voltage harmonic levels. The aims of the thesis have been fulfilled through a range of laboratory testing, computer simulation. Field monitoring conducted in conjunction with theoretical work was used to verify simulation studies.

Chapter 2 presented a literature review which investigated the potential power quality impacts of the domestic load on the electricity distribution system. This literature review identified the trends in appliance type, size and mix in domestic loads over the past decade. The literature review also identified that the domestic load has the potential to have a significant impact on distribution system power quality levels. Overall, the literature review found that there are relatively few studies which examine the potential impacts of modern domestic loads on distribution system power quality. Many of those that do are now quite dated possibly limiting their relevance to the modern case. All indications are that the characteristics of domestic loads have changed considerably over the last decade due to the proliferation of electronic equipment supplied through power electronic front ends. Those studies which were more up to date generally only examined the effects of a specific type of load in isolation ignoring the contributing effects of other load types both single-phase and three-phase. This produces an oversimplified view of the load electrical characteristics which may not reflect actual real world conditions. Studies clearly indicate that diversity and attenuation are very important factors in predicting the behaviour of distributed single-phase power electronic loads. Given the limitations of the available literature, it was clear that there is considerable scope for detailed investigations into the impact of modern domestic loads on distribution system power quality.

Chapter 3 of the thesis examined the electrical performance of compact fluorescent lamps. Special emphasis has been placed on the performance of CFLs throughout
This project. This is because political decisions banning traditional incandescent lamps have ensured that penetration of CFLs has risen from very low levels to very high levels over a very short period of time. The CFL is a non-linear load and there is considerable concern within the electricity distribution industry that mass penetration of CFLs could lead to increased voltage harmonic levels. Of particular concern is the potential of CFLs to interfere with load control systems which utilise signalling frequencies close to harmonic orders.

Chapter 3 detailed the electrical performance of 25 CFLs which were laboratory tested under well controlled conditions for a range of supply voltage conditions. When tested using an undistorted 230 V RMS input voltage source, it was found that most CFLs are a highly non-linear load, characterised by highly distorted input current waveforms and high input current THD. The strong exception to this is the performance of the high power factor CFL which was considerably superior in terms of harmonic current to that of all other CFLs which were tested. In general, the CFLs were found to have high displacement power factor, but poor true power factor.

Testing of CFLs showed that there is considerable variation in the electrical performance of CFLs across the various manufacturers. Further, it is also evident that the majority of CFLs do not behave like traditional switch mode power supply loads. Switch mode power supply loads are characterised by high magnitudes for low order harmonics which reduce rapidly as harmonic order increases. However, many CFLs are characterised by significant current harmonic magnitudes up to very high orders; in some cases to the 49th order, which was the limit of measurement.

The CFLs were also tested for compliance with the relevant Australian Standard that governs harmonic emissions, IEC61000.3.2 [9]. Of the 25 CFLs tested only one, lamp P, passed the first criterion of the standard based on strict power-related harmonic limits. When tested to the second less stringent criteria, 18 (72%) of the CFLs passed. This left 7 (28%) lamps which failed the standard outright. Table 4.17 showed a summary of the performance of each CFL with respect to the limits specified in AS/NZS61000.3.2.
Analysis was also made of performance of the CFL under varying input voltage magnitude and harmonic distortion levels. On the whole, the harmonic distortion of the input voltage as opposed to changes in the input voltage magnitude has the greater impact on CFL input current performance.

The electrical performance of a range of other modern domestic appliances was examined though laboratory investigations detailed in Chapter 4. Based on the performance for undistorted rated input voltage, the following are noteworthy results arising as a result of test carried out:

- Modern televisions, plasma and LCD types, have significantly better performance with respect to harmonic current emission compared to their CRT predecessors in spite of having higher rated power levels.

- Modern, inverter air-conditioners have harmonic emission performance much better than first generation inverter types.

- The performance of the PC reflects that of a traditional simple switch mode power supply. This is the only relatively high power device to have this characteristic.

- Low power rated devices such as the DVD player appear to be supplied using simple switch mode power supplies and have input current harmonic spectrums to match.

The appliances assessed in Chapter 4 were subjected to the same variations in input voltage magnitude and distortion levels as were applied to the CFLs. Results of these tests indicate that the basic input current characteristics of the appliances tested are relatively insensitive to changes in the magnitude of the undistorted supply voltages. Investigations completed using distorted input voltages indicated that the input current characteristics of most devices were highly sensitive to distortion in the input voltage. Harmonic distortion of the input voltage was found to have a much greater
impact on the input current of each appliance than was the case for changes in undistorted supply voltage magnitude.

Computer simulations were used to apply the results of the laboratory testing reported in Chapters 2 and 3 to a realistic electricity network model in order assess the impact of the modern domestic load on distribution system power quality levels. Chapter 5 of the thesis described the development of the simulation model. A flexible model was developed allowing a range of feeder lengths and loading scenarios to be implemented. These scenarios attempt to reflect the diversity of practical electricity networks.

Chapter 6 of the thesis presented the outcomes of the computer simulation. The simulations were designed to indicate the impact of local load on local harmonic levels and as such upstream (i.e. MV and HV) influences have been discounted. Overall, the majority of model results were found to be reflective of credible harmonic magnitudes and profiles. Results most reflective of contemporary field observations were obtained by using models where the injected current levels were based on measurements of appliance behaviour when supplied with distorted input voltages as opposed to sinusoidal input voltages. This is expected since undistorted input voltages are very unlikely to be seen in practice.

On the whole, results indicate that very high penetration (i.e. large numbers in each residence) of modern domestic appliances will result in harmonic voltage levels on low voltage feeders that will exceed Australian harmonic voltage planning levels. The models also indicated that the profile of the harmonic voltages due to modern domestic appliances may not be the same as the traditional profile where low order harmonics dominate. There is evidence to show that if high penetration of modern appliances occurs on low voltage feeders the dominant voltage harmonics due to interaction of load currents associated with those loads with network impedance may be the 7th or 15th harmonic.

Special emphasis has been placed on the impact of CFLs on harmonic levels in Chapter 6. Results of modelling clearly show that a significant number of CFLs can
have an important impact on voltage harmonic levels. Compared to the case where no CFLs were included in load models, the following can be said of CFLs:

- The models indicate that the addition of CFLs to the load will result in increased 3rd harmonic voltages levels regardless of the type of CFL used. Depending on the distortion level of the input voltage, indications are that levels may be up to 1.5 times the values obtained with no CFLs.

- The impact of the CFLs on 5th harmonic levels was dependant on the CFL type and the input voltage scenario. There was no consistent behaviour observed across all scenarios with some scenarios leading to increases in 5th harmonic voltage while others lead to decreases. Regardless of whether an increase or decrease was observed, the impact of CFLs on 5th harmonic levels was not as significant as that observed for 3rd harmonic levels. Given the variation in results it seems likely that the impact of CFLs on 5th harmonic levels may be minimal and would likely be difficult to identify in any case.

- Depending on the input voltage scenario, very large increases in 15th and 21st harmonic voltage levels may be observed if the penetration of some types of CFLs is large. There is concern in the electricity distribution industry that these high harmonic voltages at frequencies close to those used for audio frequency ripple injection load control signals may interfere with the operation of these load control systems. The results of the modelling here show that these concerns may have merit. However, the results of the models for these higher order harmonic were very large and it is unlikely that they will occur in practice. This indicates that the modelling methodology adopted is not performing as well for higher order harmonics as it does for lower order harmonics. Refining the model for higher order harmonics is an avenue for future work.

Chapter 7 of the thesis compared the harmonic levels obtained through computer simulation to existing harmonic levels at a number of sites on typical low voltage distribution feeders. These sites were specifically selected because they have characteristics similar to the network modelled in the computer simulation. There are
a number of reasons that make direct comparison of model results with field data very difficult. These include the fact that the simulated models will never exactly match actual network loading and operating conditions along with the fact that the simulations reflect an entirely modern load whereas the actual load on the network will consist of a mix of older and newer appliances.

Notwithstanding these difficulties good correlation between field measurements and model results was achieved for 3rd and 5th harmonic. Correlation between model results and field data for the higher order harmonics which were examined (7th, 15th and 21st) was not as strong.

8.2 Future Work

8.2.1 Refinement of Modelling Methodologies

In Chapter 6 of the thesis some of the simulation models developed led to harmonic voltage levels which were unlikely to be representative of those seen in practice. This indicated that the modelling methodology in some cases may need refinement. Methods of harmonic modelling can be complex, especially for higher order harmonics and if very accurate models were required, some of the assumption used in this thesis need closer examination. Further, for a complete understanding of the impact of loads on the wider electricity distribution system, modelling and assessment of underground and aerial bundled cable networks may be necessary.

8.2.2 Continuation of Field Measurements

Although a significant amount of data is available for voltage THD and 5th harmonic voltage through the LTNPQS project, little data is available at low voltage sites for other voltage harmonic orders. In addition almost no data is available for harmonic currents as most routine power quality measurement systems only measure voltage disturbances.

There is also very little data available from the remote ends of low voltage feeders. This is due to difficulties in identifying and installing instrumentation at these sites.
Mass rollouts of smart meters in Australian electricity distribution systems may provide an avenue for expanded power quality monitoring, particularly at sites at remote ends of feeders. This opportunity should not be missed and those installing smart meters should be mindful of the power quality benefits that may be obtained from such meters when they are undertaking smart meter installation.

8.2.3 Investigation of New Appliances

Energy efficiency appears to be an area of interest that will be maintained for at least the foreseeable future. This will result in more domestic appliances moving towards electronic operation as this type of operation is more efficient than traditional means. As such there is every likelihood that more and more domestic appliances will operate in a fashion that are capable of emission of and susceptibility to power quality disturbances. For example, an appliance that was once considered a passive load but is now moving toward supply through power electronics is the refrigerator.

For lighting, CFLs are presently the only cost-effective alternative to the traditional incandescent lamp. It is likely that LED technology will replace CFLs within the next decade as LED technology is maturing rapidly and prices are falling. Although LEDs are a small load individually, the impact of the many LED lighting systems use power electronic front ends which will form the lighting load may be worthy of investigation.

As new technologies emerge, studies similar to the one presented in this thesis should be undertaken in order to assess the impact of these new devices on the electricity distribution system. This will allow electricity distributors to have a continued understanding of the loads connected to the power system and their potential power quality impacts.
References


