“THE INFLUENCE OF NON-LINEAR LOADS ON THE POWER QUALITY OF THE NEW ZEALAND LOW VOLTAGE ELECTRICAL RESIDENTIAL POWER DISTRIBUTION NETWORK”

A thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering in Energy Management at Massey University, Manawatu

MICHAEL S. WITHERDEN

2012

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Acknowledgements

The author, Mike Witherden, under the supervision of Prof Ramesh Rayudu, initiated and led this postgraduate research into “The Influence of Non-linear Loads on the Power Quality of the New Zealand Low Voltage Electrical Residential Power Distribution Network”. Prof Ramesh Rayudu also supervised the work of three other students under this topic:

> **Rémy Rigo-Mariani** *“Compact Fluorescent Lamps and Power Quality*, Postgraduate Research Report, Massey University (2008).
>
> **Hien Nguyen** *“Residential Power Quality Analysis”*, BEngTech Final Year Project, Massey University (2009).
>
> **Andries Nieman** *“Harmonic Distortion Effects in Residential Homes”*, BEngTech Final Year Project, Massey University, (2009).

Their work directly informs this thesis.

The author would also like to acknowledge:

Prof Ramesh Rayudu for tirelessly supervising and encouraging the research.

Prof Neville Watson for support and access to information on Power Quality.

George William Tyler who continues to provide inspiration and both unique technical insight and unique technical solutions to complex problems.

Christopher Tyler for access to his work on Non-Invasive Load Monitoring.

The Energy Efficiency and Conservation Authority (**EECA**) for assisting with student fees.

Lisa Sinclair for tirelessly editing and re-editing of this document.

My Family for putting up with my grumpiness while I prepared this document.

List of Papers Resulting from this Research

Witherden, M.S. Tyler, G.W. Rayudu, R.K. *Innovation - Power Quality Correction Unit*, Paper presented at the National Energy Research Institute (NERI) Energy Conference, Professional / Community, Research, Wellington, New Zealand, April **2009.**

Witherden, M.S. Tyler, C. Rayudu, R.K. *Identifying Disturbing Loads in the New Zealand Low Voltage Electrical Power Distribution Network*, Paper presented at IEEE I&M Society New Zealand Chapter workshop, Massey University, Wellington, New Zealand, September **2010.**

Rigo-Mariani, R. Rayudu, R.K. Witherden, M.S. Lai, E.M., "Power quality indices of Compact Fluorescent Lamps for residential use - A New Zealand study," Paper presented at TENCON 2010, IEEE Region 10 Conference, pp.647-652, 21-24 Nov. **2010.**
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Witherden, M.S. Rayudu, R. Rigo-Mariani, R., "The influence of nonlinear loads on the power quality of the New Zealand low voltage electrical power distribution network," A paper presented at the Universities Power Engineering Conference (AUPEC), 2010 20th Australasian, pp.1-6, 5-8 Dec. **2010**.
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R. Rayudu, R. Rigo-Mariani, M. Witherden, "Effect of Multiple Compact Fluorescent Lamp Usage on Residential Power Quality," A paper prepared for IEEE Power & Energy Society, Conference on Innovative Smart Grid Technology, Asia, Perth, Australia, 13-16 November **2011.**

R. Rayudu, C. Tyler, M. Witherden, "Non Intrusive Individual Load Measurement and Identification," A paper prepared for IEEE Power & Energy Society, Conference on Innovative Smart Grid Technology, Asia, Perth, Australia, 13-16 November **2011**.

1. SUMMARY

1.1. Introduction

Most modern power supplies are non-linear loads which contain electronic devices that do not conduct current over the full cycle of the applied voltage, and so introduce harmonics into the power network. The characteristics and power quality of New Zealand's power distribution network is largely un-researched, and while it is known that non-linear loads probably decrease the power quality within the network, little research exists on the full impact these non-linear loads have, nor how disturbances from multiple non-linear loads can be mitigated cost effectively. It is also unclear how to identify and locate these many varied disturbing loads within the network. Additionally, most international power quality research, including that from Australia, tends to be based on strong networks which do not have the same high impedance characteristics as the New Zealand residential power distribution network **[1] [2]**.

Due to the need for energy saving, to reduce our dependency on non-renewable energy sources and reduce greenhouse gas emissions, New Zealand is moving away from inefficient, large, linear loads towards more efficient, smaller, non-linear loads. While the positive energy saving aspects of these non-linear loads are well known and effectively marketed, their negative aspects are not as well known and often hidden **[3]**.

The Authors participation within the AS/NZS Standards Committee EL041, played a crucial role in this research as several issues addressed in this research were initially highlighted within the committee **[12]** and in subsequent correspondence **[A7] [A8]**.

1.2. Research Aims and Objectives

1.2.1. Research Aims

1. Develop a deeper understanding of the background issues relating to power quality within the New Zealand residential power distribution network.

2. Develop an understanding of the characteristics and power quality of the New Zealand residential power distribution network.

3. Develop an understanding of the impact of the move away from the current mainly resistive residential loads to more efficient, yet potentially power quality degrading, non-linear loads, on the power quality of the New Zealand residential power distribution network.

4. Investigate techniques to locate and identify non-linear loads and measure their effects on the power quality of the New Zealand residential power distribution network.

5. Identify options to mitigate and control potential negative effects of non-linear loads, on the power quality of the New Zealand residential power distribution network.

1.2.2. Research Objectives

1. A deeper understanding of the characteristics of the New Zealand residential power distribution network.

2. An understanding of the characteristics and power quality of the New Zealand residential power distribution network.

3. An understanding of the impact of the move away from the current mainly resistive residential loads to more efficient, yet potentially power quality degrading, non-linear loads, on the power quality of the New Zealand residential power distribution network.

4. Recommended techniques to locate and identify non-linear loads and measure their effects on the power quality of the New Zealand residential power distribution network.

5. Recommended options to mitigate and control the negative effects of the impact of non-linear loads, on the power quality of the New Zealand residential power distribution network.

1.3. Research Scope and Methodology

This research investigates:

- Background issues relating to power quality.
- Characteristics of the New Zealand power distribution network.
- Drivers of the move towards non-linear loads.
- Non-linear loads characteristics and effects on power quality.
- Techniques to locate and identify non-linear loads and measure their effects.
- Mitigating power quality issues within the power distribution network.

Data was initially gathered through the review of a number of papers and other documents and communications with individuals and organisations. This research then collected new data to fill the data gaps. The power quality of a wide range of residential loads was analysed, but all direct laboratory testing done was limited to compact fluorescent lamps due to cost restraints. The Fluke 43B Power Quality Analysis tool **[A3],** consisting of a single phase power quality measuring instrument and associated software, was used exclusively within this research, to analyse the power quality of individual units and of various combinations of units both within homes and in further extensive tests within the laboratory. The Fluke 43B is the best quality instrument we could afford within our limited budget.

1.4. Research Results

1.4.1. Power Quality

Ideally, the electrical supply within a power distribution network is a perfect sinusoidal voltage waveform of constant magnitude and frequency. The degree to which the electrical power supply deviates from this ideal indicates the quality of the power system. If electrical equipment operates correctly and reliably without being damaged or stressed, the electrical power is probably of good quality. If electrical equipment malfunctions, is unreliable, or is damaged during normal usage, the power quality is probably poor.

The electricity supplier is responsible to maintain the quality of their supply, but it is the user that has to ensure that their equipment does not reduce the network power quality **[7]**.

Loads and Power Quality

Resistive linear loads only affect the amplitude of the network voltage and reactive linear loads, which contain inductive and capacitive components, affect the phase relationship between the supply voltage and current. But most modern domestic loads are non-linear and cause a number of disturbances within the network. Non-linear loads are also more sensitive to poor power quality than linear loads. So, as the number of non-linear loads has increased within the network, power quality issues have arisen.

Measuring Power Quality

Power utility companies are required to provide a network system voltage within tight limits. So, as the use of non-linear loads is increasing, measuring the power quality within the network has become increasingly important. The most common method of measurement used are:

Power Factor

Displacement power factor is the ratio of the true power used by the load and the power provided by the utility. Displacement power factor is only relevant for purely sinusoidal systems and will lead to errors if applied to non-linear loads.

True power factor is a better measure of power quality when non-linear loads are present, and is the ratio of true power to the apparent power, which takes into account both the phase shift and the wave-shape distortion.

Industrial sites use capacitors for correcting power factor, which saves on utility penalty charges. While domestic users may be required to maintain high power factor, they are currently not monitored and so not individually penalised for low power factor.

Harmonic Distortion

Total harmonic distortion (THD) is the ratio between the sum of all the rms values of the harmonic components and the fundamental component expressed as a percentage. Harmonics cause losses within the power distribution network; have significant effects on distribution equipment; and can lead to increased costs due to increased maintenance, failures, or device de-rating. Domestic users are currently not monitored or individually penalised for high harmonics, but their loads are required to comply with the national harmonic limits.

Other Measures of Power Quality

K Factor rating is used by power companies and transformer manufacturers to establish a link between harmonics and the losses they cause in a particular transformer.

Crest factor (CF) is defined as the ratio between the peak value of a signal and its rms value, and is one of the simplest measures of distortion within a network.

POWER QUALITY REGULATIONS STANDARDS & LIMITS

Utilities require users to keep their harmonics within the NZECP 36 limits. They also require that customers maintain a power factor of greater than 0.95, and consumers may incur a penalty charge if they cannot meet the power factor limits **[7]**.

Watson **[12]**, expressed concerns regarding the effects of non-linear loads, and in particular CFLs, on power quality within New Zealand, and the inappropriateness of relevant local standards in dealing with this issue. Peter Morfee from the Ministry of Economic Development (MoED) **[A8]** stated that CFLi's may be a problem and that he is taking action by requesting that AS/NZS61000.2.3 is modified with respect to CFLi's.

The Electricity (Safety) Regulations 2010 **[9]** **[A5]** refer to ECP 36 - the New Zealand Electrical Code of Practice for Harmonic Levels **[10]** and also to IEC 61000.3.2, the International Harmonics Standard **[16]**. But not to AS/NZS 61000.3.2:2007 **[15]** **[A1]**, or the more stringent AS/NZS 61000.3.2:2007 Amt A, 2009, local Harmonic Standard **[17]** **[A2]** which was specifically updated to reflect our local requirements. This is probably due to strong lobbying from the lighting industry.

1.4.2. CHARACTERISTICS OF NEW ZEALAND RESIDENTIAL NETWORK

The New Zealand residential power distribution network is made up mainly of high voltage AC transmission lines, but also includes a high voltage direct current link carrying up to 1 GW from the South Island to the North Island and up to 0.6 G MW in the opposite direction. This link is split into two poles and a third pole is under construction [21]. The old 1960s mercury arc valve technology of Pole 1 currently injects high levels of harmonic distortion into the New Zealand residential power distribution network.

Both the voltage and the current waveforms within the New Zealand residential power distribution network deviate markedly from true sine, which indicates low power quality probably due to the local residential power distribution network being “weak” having a high impedance, which is probably because of the long distances between the main generators and the main loads, and because of the “spread out” nature of settlements in New Zealand. The power quality of weak networks is sensitive to non-linear loads, so energy saving initiatives using non-linear loads result in lowering the power quality in such networks [2].

Total harmonic distortion within the New Zealand residential power distribution network is already near the upper limit of 5% [10] and limited local research indicates that non-linear loads have a current waveform that is rich in harmonics which distorts the voltage waveform of the residential power distribution network even further. The full impact of the harmonics from the widespread adoption of non-linear loads is concerning as it is diverse and subtle and there is little recent research available on this topic.

Although domestic users should face a penalty if they cannot maintain a power factor above 0.95, they are not usually measured for harmonics or power factor, but the recent installation of ‘smart’ power meters will give utilities the ability to easily measure domestic user’s harmonics and power factor.

1.4.3. Drivers of Move to Non-linear Loads

There is a growing proliferation of high reliability, low cost non-linear electronic products, and it is getting harder to find linear loads in Australasian homes [2]. The drivers that have resulted in this proliferation are a direct result of the availability of low cost switch mode devices and control circuitry, as well as the benefits that such technology can bring to end users such as lower operating costs, smaller size, weight reduction and improved performance [23]. Other important drivers are the government led energy efficient campaigns intended to reduce pollution from fossil fuel generation of electricity through reducing overall load.

1.4.4. Non-linear Loads Characteristics and Effects

The electronic front end of non-linear loads makes them more efficient than linear loads **[2] [3]**.

As product cost is usually proportional to component count, the most common front end design used by manufacturers of modern electronic devices globally is a simple non-linear rectifier and capacitor circuit which converts the supplied AC voltage into DC to power a wide range of household appliances, lighting units, and chargers. Unfortunately these non-linear front ends are a common source of harmonics **[12]**.

A simple way of improving the converters power quality is to use passive filtering. This is simple to implement and the more extensive the filtering is, the better the AC current waveform, but the higher the cost, physical size and weight.

A more complex "valley fill" front end further reduces the harmonic distortion to acceptable levels, but adds more complication and cost to the final product. However, this circuit produces both lamp power and light output fluctuation and reduces lamp life. A further improved valley-fill circuit gives a reasonably cost effective way of improving power factor as well as reducing the harmonic current levels.

The most complex solution uses an active 'power factor correction' circuit which eliminates harmonic distortion, but adds the highest cost to the final product. This additional cost is small in absolute terms but becomes significant in very low cost devices such as Compact Fluorescent Lamps (CFLs) **[12]**.

1.4.5. Interaction Between Multiple Non-linear Loads

Hardie & Watson **[20]** found that harmonic phase angle diversity is relevant when multiple appliances are operating simultaneously, creating either reinforcement or cancellation of harmonic magnitudes. The very low harmonic angle diversity in CFLs suggests that multiple CFLs should be considered as a single high power load with corresponding high harmonic current distortion.

They also simulated the harmonic impact of the appliances tested on a typical distribution network and concluded that; "The range of appliances tested and measured shows that many of the loads being connected to the network today create moderately significant current harmonics. While the power of most of these devices is low, the large and increasing numbers of appliances with low harmonic angle diversity means that harmonic voltage levels are likely to rise in the future within Low Voltage (LV) and Medium Voltage (MV) distribution networks." Hardie & Watson **[20]** conclude by explaining that present linear loads are being replaced by non-linear appliances. For example, water heating heat pumps are replacing conventional resistive hot water cylinders and domestic fridge/freezers now sold that use a compressor motor with Variable Speed Drive (VSD,) instead of a standard direct on line compressor motor. These new appliances are likely to accentuate the harmonics issues **[20]**.

1.4.6. Locating and Identifying Disturbing Loads

The measurement of the power quality of multiple loads is difficult, intrusive, and expensive, as identifying each individual disturbing load in the domestic power distribution network usually requires us to measure each load separately.

A simple way of identifying each load is to measure the step changes in real power at the point of common coupling to recognize which load is on. But it is not possible to differentiate between loads by simply measuring step changes in real power as many domestic loads have the same real power.

A slightly more advanced method of identifying each load is to measure the step changes in both real and reactive power. However, although this technique is common and has been developed commercially, it cannot differentiate between devices with similar real and reactive power signatures.

The approach finally proposed in this research way to identify each load using the distinct harmonic signature of each load. Measurement needs to be at a sampling rate approaching 10 kHz, and then analysis by software enables differentiation between an almost infinite range of load signatures.

With this method, no access to the individual loads is necessary for installing sensors or making measurements. This provides a very convenient and effective method of gathering load data compared to traditional means of placing sensors on each of the individual loads. So, by a sophisticated analysis of the current drawn by the total load, the software identifies the individual loads, and their daily time of use profile.

The resulting end-use load data is extremely valuable to consumers, energy auditors, utilities, public policy makers, and appliance manufacturers for a broad range of purposes, as a monitor placed at one point can determine how much energy goes into each of the individual loads within the home.

1.4.7. Compact Fluorescent Lamps as Representative Loads

Compact fluorescent lamps (CFLs) are used in this research as a representative example of modern non-linear loads as they exhibit the typical characteristics of all modern loads, but are low cost and consume low power, around 20 Watts, making them easier to study within the limited budget of this research.

CFLs have several advantages over equivalent traditional linear lighting loads; they are about 75% more efficient and may last about 6 times longer. However, as the use of CFLs increases, power quality issues such as increased harmonic voltage levels and reduced power factor are expected to rise **[14]**. The main issue looked at in this research is the high level of harmonic current CFLs inject into the residential power distribution network.

The most well known high quality local CFLs achieve a power factor of over 0.9 and low total harmonic distortion by using a 'valley-fill' ballast circuit. Unfortunately most local CFLs use only the simplest basic ballast circuit, mainly because of its lower cost.

CFLs Harmonic Interaction

A range of experiments were conducted on a diverse set of locally available compact fluorescent lamps. The lamps could clearly be classified into low power factor (LPF) and high power factor (HPF) lamps with low power factor lamps having correspondingly high harmonic distortion. Testing found that when lamps were combined, harmonic addition even with lamps of the same type, were not linear and that the interaction between low and high power factor lamps was complex and the inclusion of high power factor lamps partially 'canceled' the harmonics produced by low power factor lamps.

CFLs Harmonic Limits

Besides complying with local safety and performance standards, CFLs are also expected to comply with local power quality standards. However a clause in the local performance standard means that CFLs only need to comply with much more lenient requirements than other similar devices.

Recently the local harmonics standard, AS/NZS 61000.3.2:2007 Amt A 2009 **[17]**, was amended to make the limits for CFLs more stringent **[A2]**, but this new clause is not called up in any local standard due to strong lobbying by the lighting industry.

1.4.8. Mitigation

This research has ascertained that the New Zealand Power Distribution Network has low power quality and is 'weak' having higher impedance than most first world countries **[11]**. Several mitigation options were looked at and it is suggested that strengthening the network and improving the power quality are urgently required.

Upgrade to HVDC Link

The long awaited upgrade to the High Voltage DC Link (HVDC Link) will not only strengthen the 'weak' New Zealand power distribution network, but also reduce the 'background' harmonic distortion currently injected into the network by the old 1960s mercury arc valve technology of Pole 1 **[11]**. The HVDC grid upgrade has THREE Stages:

Stage 1: Due by 2012, is a new Pole 3 to replace the existing Pole 1, bringing capacity up to 1000 MW.

Stage 2: Due by 2014, will enable bi-pole operation up to 1200MW.

Stage 3: Due beyond 2017, will increase overall capacity of the link to 1400 MW.

Network Power Quality Correction

Generally, the distortion caused by small non-linear loads has been ignored, yet the combined effect of the wholesale introduction of small, non-linear loads can be even more detrimental than one large distorting load acting as a harmonic source because the power quality requirements for small loads are much less stringent than for large ones. A further complication is that mitigation of the harmonic distortion caused by multiple small non-linear loads is also very difficult once they are in the network due to the dispersed nature of these loads within the network [3].

Power factor correction and harmonic filters can be retrofitted at or near large disturbing loads, but it is not as easy to retrofit them onto each small disturbing load, so they are usually installed at common connection points higher in the network. However the most cost effective way is to ensure that only high power quality non-linear loads are installed, as correcting the problem higher up in the network costs up to 10 times more than the cost of selecting high quality loads in the first place [24].

Residential Power Quality Correction

Many small devices are being connected onto the residential power distribution network and as these small devices have less stringent harmonic requirements, and as these devices are often installed in large numbers at the same location, they will continue to present a considerable disturbance within the New Zealand residential power distribution network.

As part of this research, a power quality correction unit is proposed to reduce the distortions caused by non-linear loads as close to the source as possible, either within or at the source or at the first point of common coupling. This then reduces the need to install expensive, large, power quality correction devices higher up in the network. The unit corrects power distortions such as power factor, phase, frequency and harmonic distortion, improving the power quality of the load/s it is connected to and so improves the power quality of the power distribution network.

1.5. Conclusions

The old Pole 1 of the DC link injects high levels of background harmonic distortion into New Zealand residential power distribution network which has high impedance making it sensitive to non-linear loads, but fortunately, the current upgrade to the High Voltage DC Link when complete will strengthen the New Zealand power distribution network and reduce the ‘background’ harmonic distortion.

The current move away from linear loads to more efficient non-linear loads is decreasing power quality and will probably increase total harmonic distortion to over the 5% New Zealand limit, creating a potential for faults and troubles within the network.

The origins and effects of power quality problems are very diverse as most modern electronic devices are non-linear and have adverse effects on distribution equipment and other loads, causing failures, devices de-rating, or increased maintenance costs. Mitigation of harmonic distortion caused by multiple small non-linear loads is very difficult once they are in the network due to the dispersed nature of these loads within the network.

The electricity supplier has the responsibility to maintain the quality of their supply within specified limits, but it is the users that have to ensure that their equipment can withstand power disturbances, and it is also the user that must ensure their equipment does not cause any disturbances within the power distribution network.

Non-linear loads are more efficient than linear loads, but they are a common source of harmonics. This can be improved by using passive filtering but this increases cost, size and weight. A ‘valley fill’ front end further improves power quality, but adds more complication and cost. Multiple small loads with low harmonic angle diversity should be considered as a single high power high harmonic distorting load. Measuring individual loads requires intrusion on each load to install complex hardware so it is more cost effective to measure at the point of common coupling, identifying the distinct harmonic signature of each load, and measuring their end-use load profile. This data is extremely valuable for a broad range of purposes.

High quality CFLs have high power factor and low total harmonic distortion, but most manufacturers still produce low quality CFLs which have low power factor and high harmonic distortion. Harmonic addition and the interaction between low and high power factor lamps is complex as the addition of high power factor lamps partially cancels out the harmonics produced by low power factor lamps. CFLs only need to comply with much more lenient requirements than other similar devices. The local harmonics standard was amended to make the limits for CFLs more stringent, but this new clause is not called up in any local standard due to strong lobbying by the lighting industry.

A power quality correction unit is proposed to reduce the distortions caused by non-linear loads as close to the source as possible. The main benefit of this unit is improvement to the power quality of the local device it is connected to and also improve the power quality of the power distribution network it is connected to and so reduce the need to install expensive, large, power quality correction devices higher up in the network, which costs up to 10 times more than correcting the problem at each disturbing load at manufacture.

1.6. RECOMMENDATIONS

Extended future investigations and mitigation initiatives are needed nationally, especially in areas where the residential power distribution network is the weakest, to quantify and qualify the extent of the influence of non-linear loads on the power quality of the New Zealand low voltage electrical residential power distribution network.

Utilities, manufacturers and policy makers need to monitor the power quality issue and work together to develop and/or review standards and regulations, focusing on power factor and harmonic distortion issues.

Regulators need also to ensure that they police energy using products to ensure that there is compliance with New Zealand's local specific power quality requirements, as local New Zealand requirements differ from the requirements of other first world countries, and even differ from Australia's power quality requirements. This is due not only to New Zealand's 'weak' power distribution network, but also to the already appreciable background harmonics levels within the network.

Intensive initiatives encouraging the use of non-linear loads should include harmonic filtering and power factor correction techniques, and/or consideration needs to be given to incentives to overcome the initial higher cost of higher quality non-linear loads.

2. INTRODUCTION

Most modern power supplies, in almost all of the many electronic devices found in New Zealand homes, are non-linear loads which contain electronic devices that do not conduct current over the full cycle of the applied voltage in sinusoidal AC circuits, so their current waveform is not sinusoidal. These non-linear loads introduce harmonics into the power network which cause a number of disturbances such as voltage waveform distortion, over heating in distribution equipment, and heating in neutral conductors to list just a few.

The characteristics and power quality of the New Zealand power distribution network is largely un-researched, with scarce information available, so there is limited understanding of the full extent and effect of the harmonics caused by non-linear loads in the residential power distribution network. While it is known that non-linear devices probably decrease the power quality in a power distribution network, little research exists as to the actual effect these disturbing loads will have. Nor is it clear how disturbances from these multiple modern non-linear loads can be easily and cost effectively mitigated. It is also unclear how to identify and locate these many varied disturbing loads within the network. Additionally, most international power quality research, including that from Australia, tends to be based on strong networks which do not have the same characteristics as the New Zealand power distribution network. As multiple smaller non-linear loads increasingly replace large linear loads, the combined effect will become detrimental and hard to mitigate due to the widely distributed nature of these many small, disturbing non-linear loads **[1] [2]**.

As a response to the need for energy saving to reduce our dependency on non-renewable energy sources and to reduce greenhouse gas emissions, both New Zealand and Australia are reducing electricity consumption by moving away from inefficient large linear loads towards more efficient smaller non-linear loads. This is because the electronic front ends of these non-linear loads make them more efficient than linear loads. While the positive energy saving aspects of these non-linear devices are well known and effectively marketed, the negative aspects of these non-linear devices are not as well known and are often hidden. It is therefore important to find out if modern non-linear loads are further weakening the New Zealand power distribution network. With the increasing number of non-linear loads in use, understanding and analysing power quality issues has become a challenge **[3]**.

Measuring and analysing the effects of non-linear loads on the power quality of the New Zealand residential power distribution network is not enough however, knowing which load is used when is crucial. But identifying disturbing loads within the power distribution network is difficult, so this research also considered potential ways of identifying disturbing loads within the residential power distribution network.

This research analyses the available local information on the effects, (on the power quality of the weak New Zealand residential power distribution network), of moving towards non-linear loads. New demand side data needed to be collected and interpreted in order to fill the existing data gaps to provide a helpful source of information for extended investigations and mitigation initiatives in future.

Further research conducted into mitigation options proposes an innovative solution to develop a device for connection to the power distribution network near disturbing loads to reduce the distortions created by these non-linear loads.

A presentation to the March 2008 meeting of the AS/NZS Standards Committee EL041 **[12]**, of which the Author is an active member, and subsequent correspondence between the Chairman of AS/NZS Standards Committee EL041-08 **[A7]**, and the Ministry of Economic Development (MoED) **[A8]**, played a crucial catalyst role in this research and highlighted several issues addressed in this research.

3. RESEARCH SCOPE AND METHODOLOGY

This research investigates:

- Background issues relating to power quality
- Characteristics and power quality of the New Zealand residential power distribution network.
- Drivers of the move towards non-linear loads within the power network.
- Non-linear loads characteristics and effects on the power quality of the network.
- Interaction between multiple non-linear loads on the network.
- Techniques to locate and identify non-linear loads and measure their effects.
- Compact fluorescent lamps as representative modern loads.
- Mitigating power quality issues on the network.

Data was initially gathered through paper reviews, standards, regulations, codes of practice and other documents as well as conversations and communications with organisations and individuals. In order to fill the data gaps, this research collected new demand side data through measurements in the laboratory and in individual homes.

The power quality associated with a wide range of loads was analysed and the disturbing loads identified. The effects of harmonic interaction were also explored through laboratory testing.

Due to cost constraints the detailed laboratory experiments were limited to compact fluorescent lamps as a representative non-linear load. However extensive use was made of data from testing conducted by other local researchers on a wider range of typical non-linear loads.

The Fluke 43B Power Quality Analysis tool **[A3],** consisting of a single phase power quality measuring instrument and associated software, was used exclusively within this research, to analyse the power quality of individual units and of various combinations of units both within homes and in further extensive tests within the laboratory. The Fluke 43B is the best quality instrument we could afford within our limited budget.

4. POWER QUALITY

4.1. IDEAL POWER QUALITY

The degree to which an actual electrical power supply deviates from an ideal supply indicates the quality of the power system. Ideally, the electrical supply is a perfect sinusoidal voltage waveform of constant magnitude and frequency. However, because the impedance of the supply system is not zero, and because of the large variety of loads encountered, the reality is quite different as can be seen in **Figure 1.**

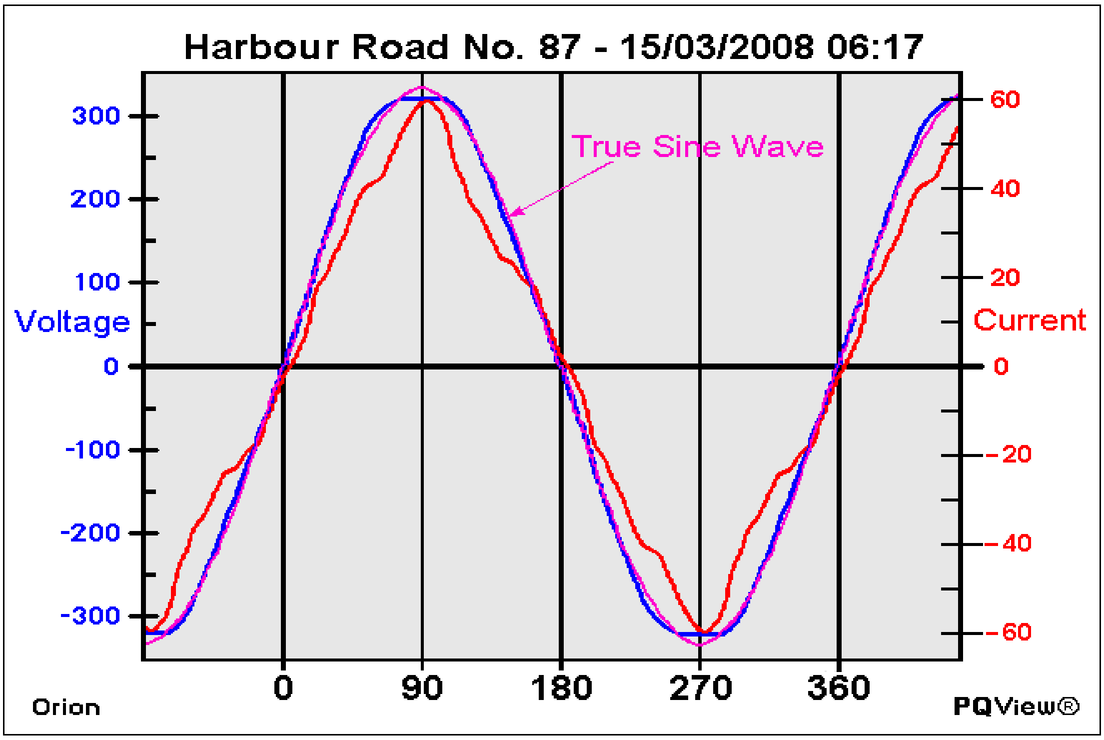


Figure 1. Voltage (Blue) and Current (Red) waveforms at a typical New Zealand distribution transformer [22].

4.2. IMPORTANCE OF POWER QUALITY

If the power quality of the network is high, then any loads connected to it will operate satisfactory and efficiently. But if the power quality of the network is low, then loads connected to it may fail or have a reduced lifetime, and the efficiency of the electrical installation will reduce.

If electrical equipment operates correctly and reliably without being damaged or stressed, we would say that the electrical power is of good quality. On the other hand, if the electrical equipment malfunctions, is unreliable, or is damaged during normal usage, we would suspect that the power quality is poor.

4.3. POWER QUALITY DISTURBANCES

There are four main types of power quality disturbances; amplitude, frequency, phase and waveform.

Amplitude disturbances change the amplitude of the network voltage outside its normal working range as shown in **Figure 2.**

Frequency disturbances change the supply frequency outside its normal operating limits as shown in **Figure 3.**

Phase disturbances change the phase relationship between the supply voltage and current outside its normal operating limits as shown in **Figure 4.**

Waveform disturbances cause distortion in the normally sinusoidal wave shape of the supply as shown in **Figure 5.**

Power quality problems can originate from within the supply system, from the user's load, or from a nearby load. The effects of these disturbances can be anything from overheating of network components, overstressing insulation, flickering light, equipment malfunctioning, to equipment failure.

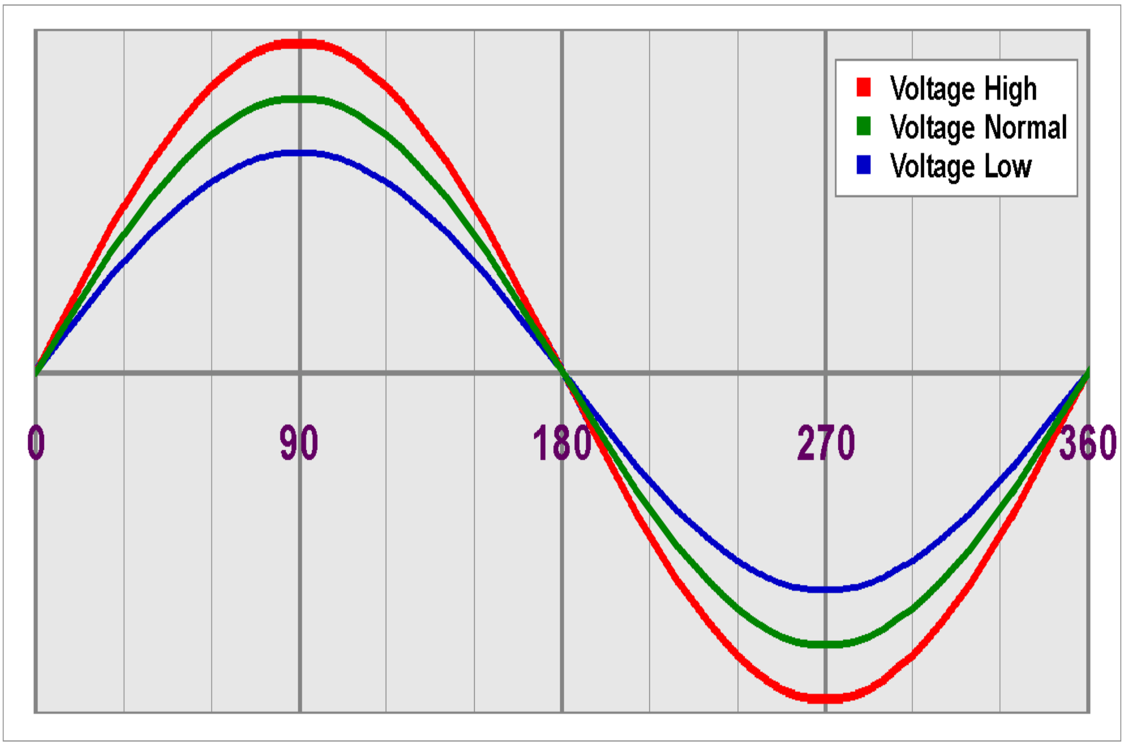


Figure 2. Amplitude disturbances.

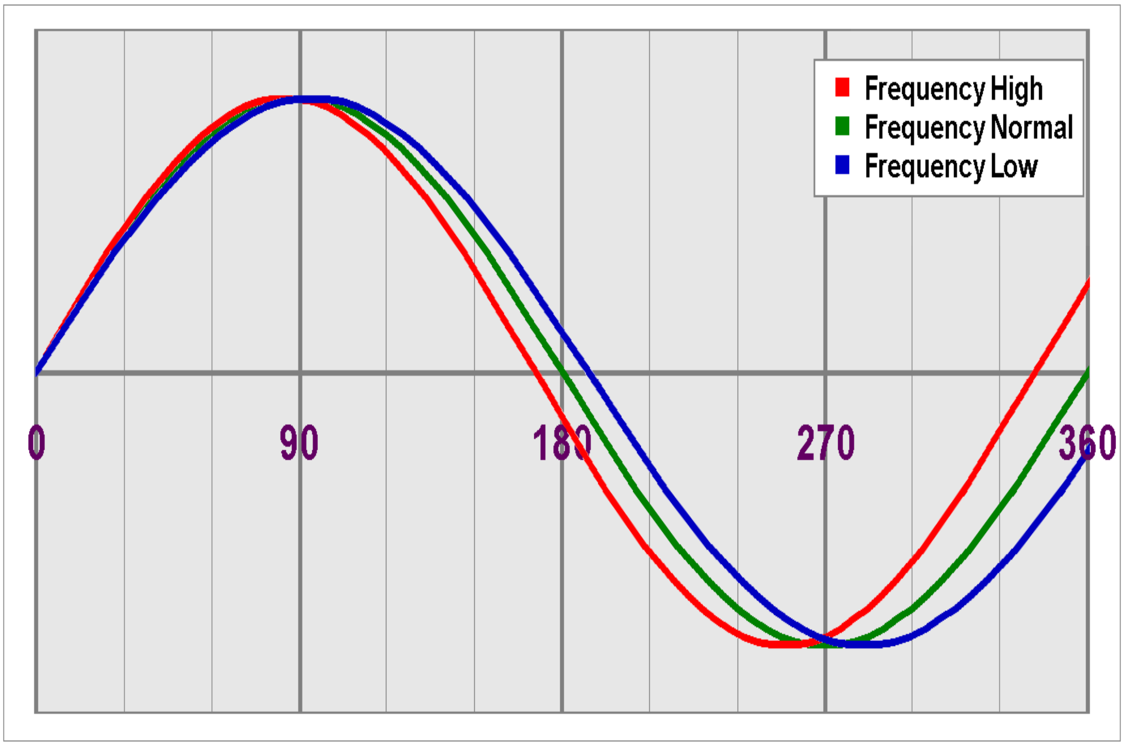


Figure 3. Frequency Disturbances.

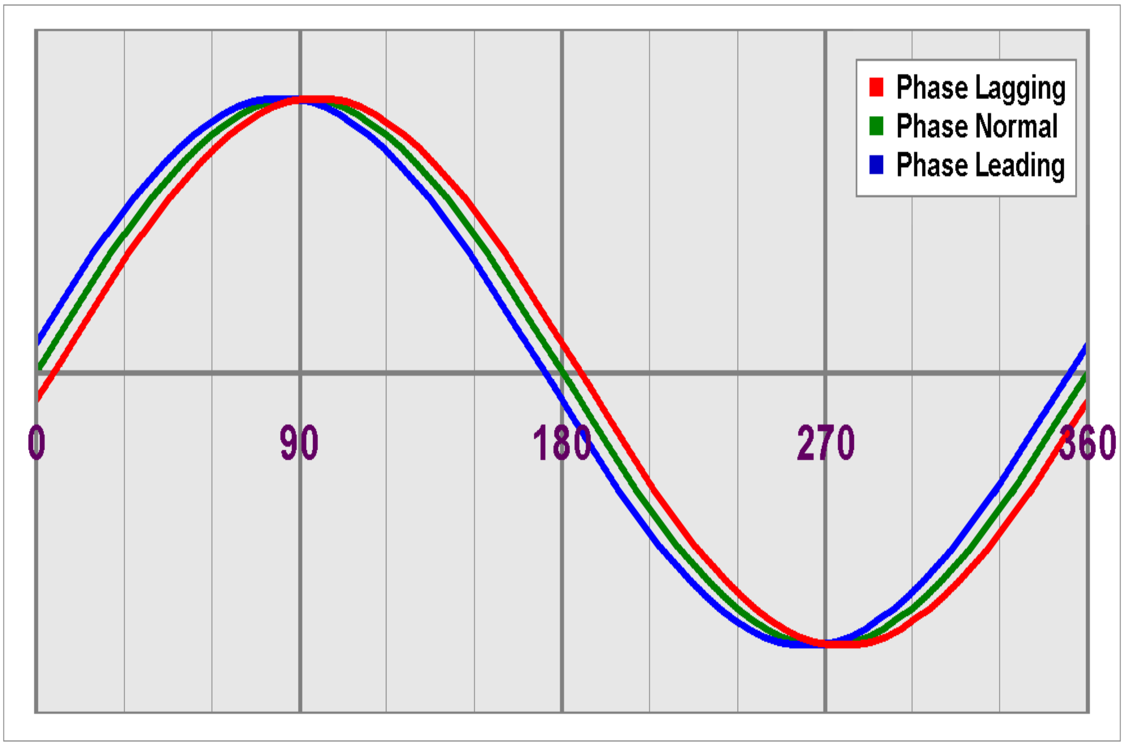


Figure 4. Phase Disturbances.

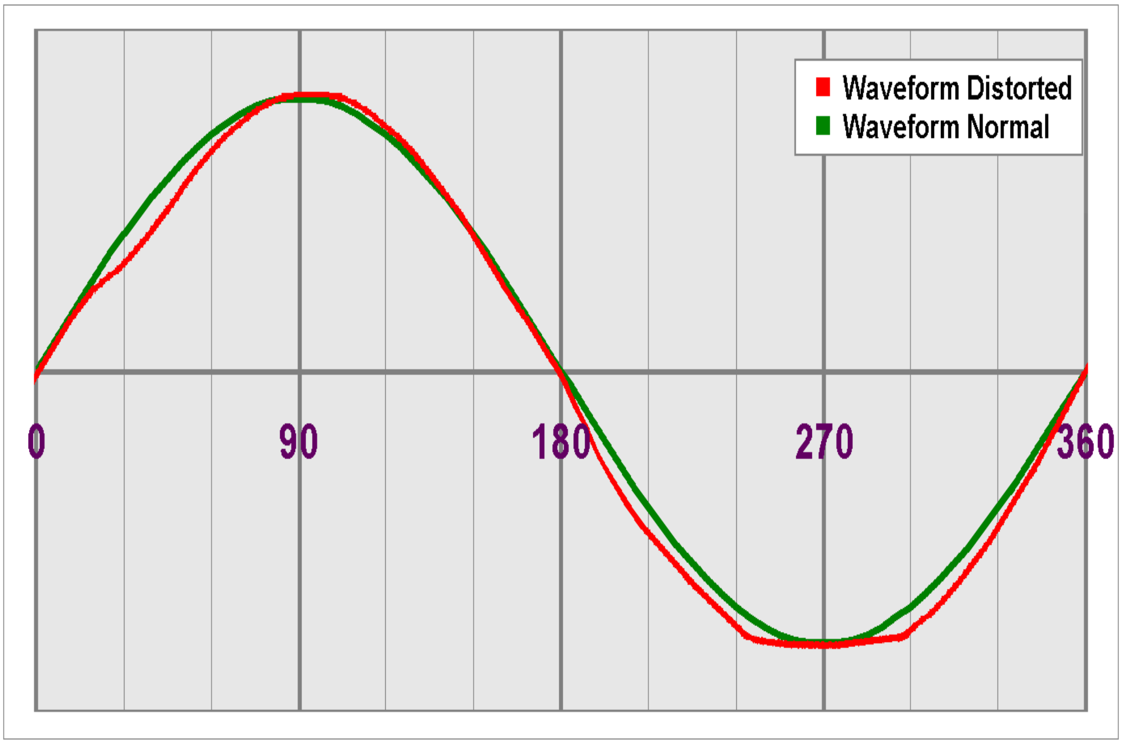


Figure 5. Waveform Disturbances.

4.4. Power Quality Regulations Standards & Limits

The effects of power quality disturbances can cause serious problems within a network, so regulations and standards have been established internationally, regionally, nationally and locally to control power quality by introducing required limits.

The electricity supplier has the responsibility to maintain the quality of their supply within specified limits. However, it is the user that has to ensure that their equipment can not only withstand normal expected power disturbances, but also that their equipment does not cause any disturbances that may propagate higher up into the power distribution network. It is the user that must ensure that their equipment does not make the power factor lower than 0.95 **[7]**.

In a presentation to the March 2008 meeting of the AS/NZS Standards Committee EL041, of which the Author is an active member, Watson **[12]**, expressed concerns regarding the effects of non-linear loads, and in particular CFLs, on the power quality within the New Zealand power distribution network, and the inappropriateness of relevant local standards in dealing with this issue. Subsequent communication between David Ford the Chairman of the AS/NZS Standards Committee EL041-08 **[A7]** and Peter Morfee from the Ministry of Economic Development (MoED) **[A8]**, highlighted several issues addressed in this research.

Peter Morfee states:

"What is before me are a series of factors that I must take into account:

- *The NZ supply network impedance is higher than that generally found in other comparable supply systems internationally. There are good reasons for this.*
- *NZ's supply system has a relatively high background harmonic distortion level. We have a lot of base load distorting equipment.*
- *NZ uses a significant amount of load control systems that can be interfered with by Harmonics.*
- *We have not adopted immunity control Standards, so we have no surety as to what levels of interference will become critical for equipment.*
- *NZ is pushing the introduction of CFLs earlier than many countries and already has a high penetration level.*

- *NZ appears to have a rapidly increasing harmonic distortion level in some locations.*
- *CFLs are given a relaxed level of harmonic restrictions by the applicable international Standard which contains two options for compliance."*

He indicates that harmonics "headroom" on our power system is rapidly reducing yet we are implementing policies that increase the rate of installation of distorting equipment, and while the increasing harmonic distortion is not from CFLs alone, their rate of installation is being pushed by the Government to exceed normal market forces. He is therefore pushing ahead with a multi-pronged strategy to strengthening the existing regulatory system for all electrical equipment; Introducing more monitoring of compliance for products in the marketplace and; Reviewing the applicable Standards for their adequacy for NZ.

He is relying on the Standards process to support him in his endeavours and has taken action by requesting that AS/NZS61000.2.3 is modified with respect to CFLi's and proposed that the relaxed limits be removed for NZ as they appeared in his opinion to allow CFLs a disproportionate allowance for distortion.

The lighting industry however indicated that these new changes could reduce the number of players and influence the competitive nature of pricing in the future, and reduce the variety of lamps that would be available.

At the start of this research in 2008 the Electricity Regulations 1997 **[8] [A4]** were in force, but by the end of this research the Electricity (Safety) Regulations 2010 **[9] [A5]** were in force.

Both the old and new regulations refer to the New Zealand Electrical Code of Practice for Harmonic Levels issued on 4 February 1993 **[10]**.

The Electricity (Safety) Regulations 2010 **[9]** also refers to IEC 61000.3.2, the International Electrotechnical Commission Electromagnetic compatibility (EMC) - Limits for harmonic current emissions **[16]**. But neither regulation refers to the local harmonic standard, AS/NZS 61000.3.2:2007 **[15] [A1]**, or to the more stringent, AS/NZS 61000.3.2:2007 Amt A, 2009 **[17] [A2]**, which was specifically updated to reflect our local requirements. This is probably due to strong lobbying from the lighting industry.

5. LOADS AND POWER QUALITY

There are two main types of loads within the New Zealand power distribution network, linear and non-linear loads, and each type has a different effect on the Power Quality within the Network.

5.1. Linear Loads

For linear loads in sinusoidal AC circuits, the ratio of voltage to current is a constant:

$$K = V_{RMS}/I_{RMS}$$

Where **K** is a constant known as Resistance or Reactance.

5.1.1. Resistive Linear Loads

Typical examples of linear loads in homes are resistive heating elements, both for space and water heating, and incandescent lamps. The voltage and current waveform in a circuit with linear resistive loads are in phase with one another as shown in **Figure 6.** Resistive linear loads affect the amplitude of the network voltage.

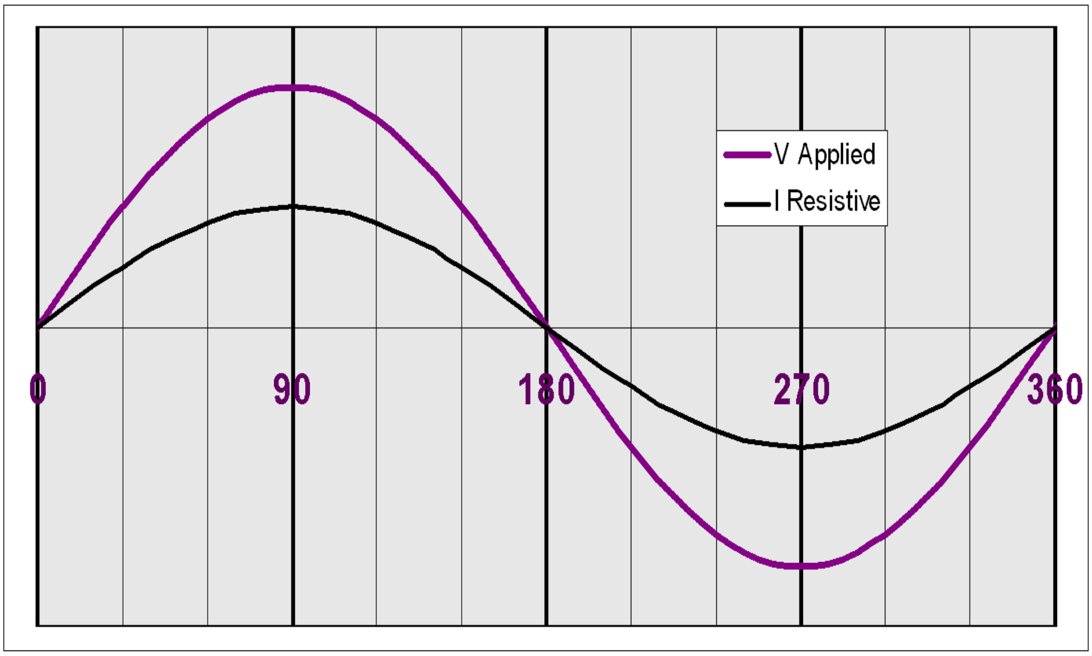


Figure 6. Resistive Load

5.1.2. Reactive Linear Loads

Reactive linear loads are loads which contain Inductive and Capacitive components. If the load is Capacitive, the current waveform will shift to the left of the voltage waveform, so the current 'leads' the voltage as shown in **Figure 7**. If the load is Inductive, the current waveform will shift to the right of the voltage waveform, so the current 'lags' the voltage as shown in **Figure 8.**

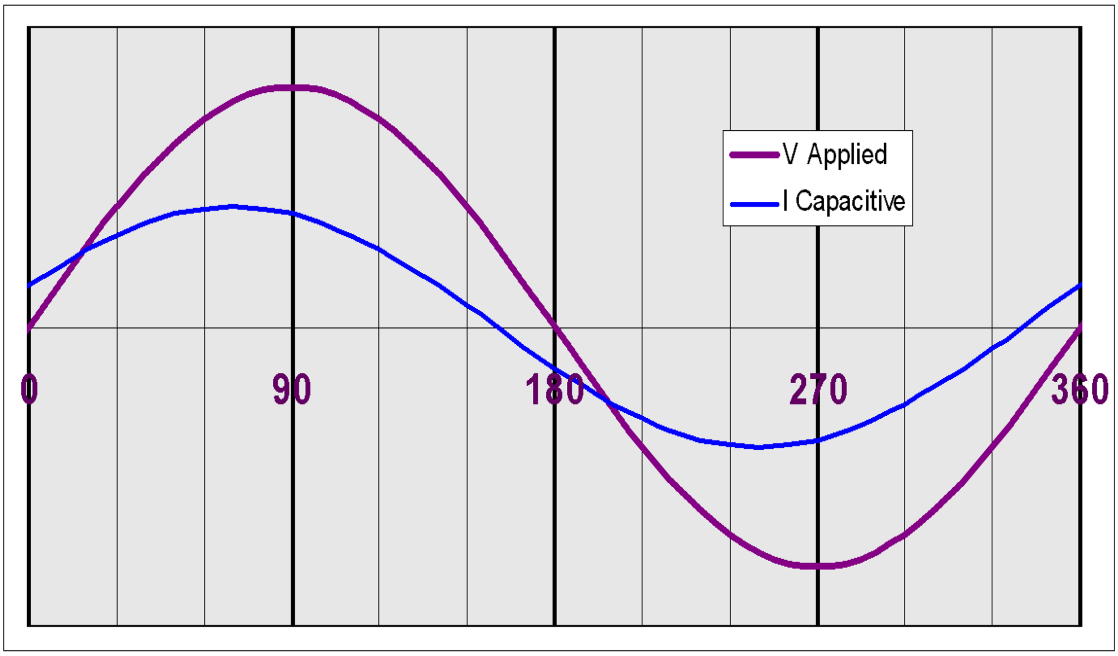


Figure 7. Capacitive Load

Therefore, for both the capacitive and inductive loads, the voltage and current waveforms are out of phase, but note that there is no waveform distortion; so reactive linear loads affect the phase relationship between the supply voltage and current.

5.2. Non-linear Loads

For non-linear loads, in sinusoidal AC circuits, the current waveform is not sinusoidal. This is usually because these loads contain electronic devices that do not conduct current over the full cycle of the applied voltage. Most modern power supplies, in almost all of the many electronic devices found in New Zealand's homes, are non-linear loads.

Non-linear loads cause a number of disturbances such as; voltage waveform distortion, over heating in distribution transformers and other distribution equipment, higher than rated currents in circuits, and heating in neutral conductors to list just a few.

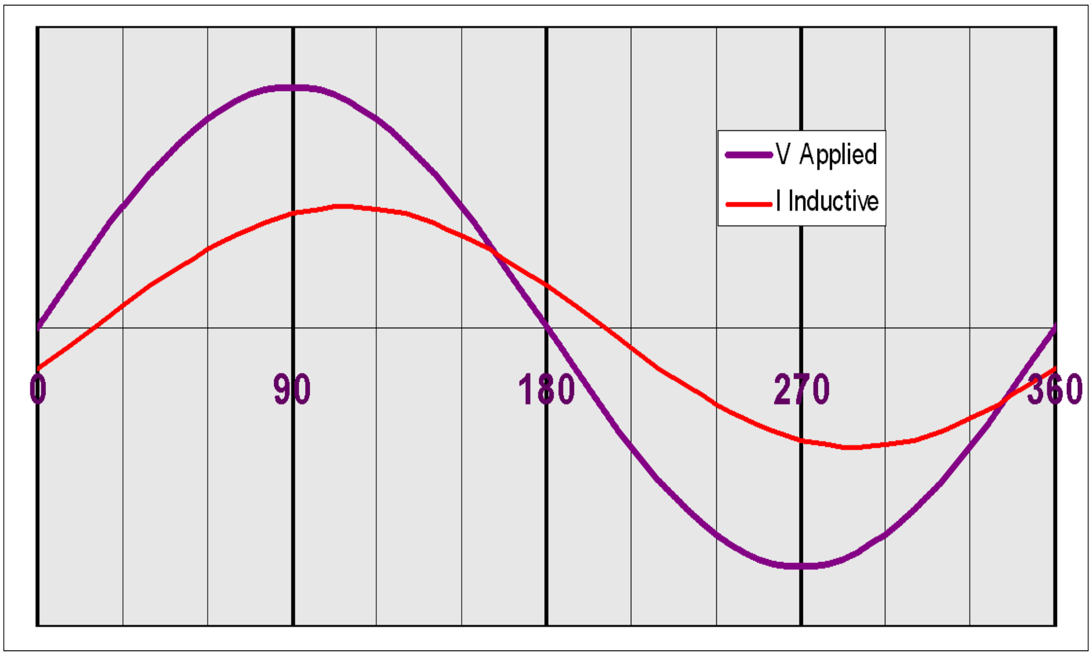


Figure 8. Inductive Load

In a typical electronic power unit, a capacitor charges for a short period forward of the peak of the voltage waveform via diodes, for the rest of the supply half cycle, the diodes are reverse biased and no current flows from the supply. The current waveform thus consists of short pulses forward of the voltage peaks, as can be seen in **Figure 9.**

As the resistance of the residential power distribution network itself is finite and not zero, drawing this non-sinusoidal current causes a corresponding change in the voltage of the residential power distribution network. Moreover, as this current is not sinusoidal, this changes the shape of the voltage waveform as shown in **Figure 10**.

Non-linear loads affect the amplitude of the network voltage, change the phase relationship between the supply voltage and current, and cause distortion to the normally sinusoidal wave shape of the supply.

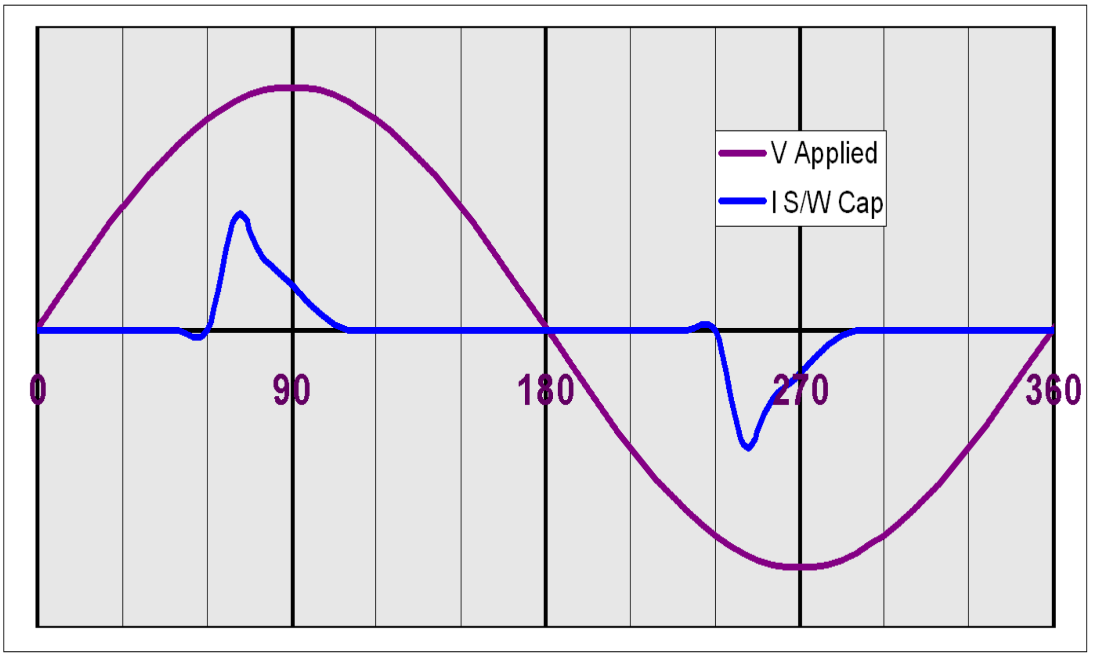


Figure 9. Switched Capacitive Load

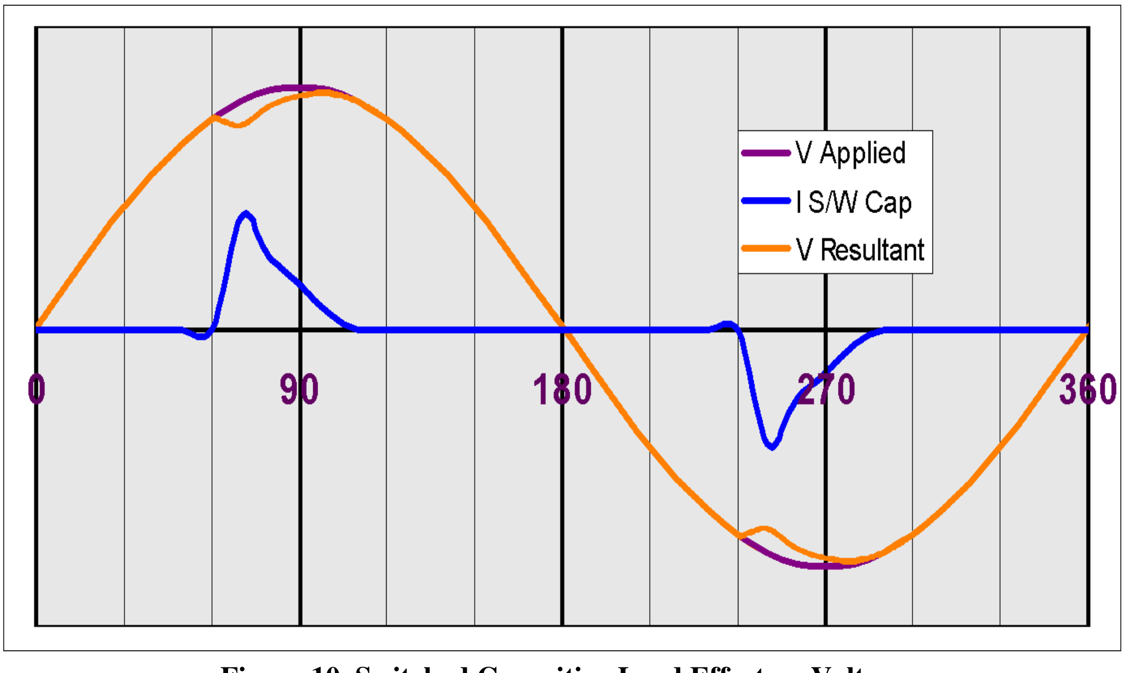


Figure 10. Switched Capacitive Load Effect on Voltage

Non-linear loads have several other issues when it comes to power quality. Not only do non-linear loads reduce power quality in a power distribution network, but non-linear loads are also much more sensitive to poor power quality in a power distribution network than traditional linear loads. So, as the proliferation of these non-linear loads has increased, power quality has become an issue that cannot be ignored.

6. MEASURING POWER QUALITY

Power utility companies are required to provide a network system voltage within tight limits. So, as the use of non-linear loads is increasing, measuring the quality of their power distribution network has become increasingly important. Many indicators are used to measure power quality, all of which help estimate the overall power quality of the network. The most common of these are discussed here.

6.1. Crest Factor

Crest factor (CF) defined as the ratio between the peak value of a signal and its rms value, is one of the simplest measures of distortion in a network. (See **Figure 11**)

$$CF = \frac{I_{peak}}{I_{RMS}}$$

For a perfect sinusoidal signal, $CF = \sqrt{2} \approx 1.41$, a more triangular wave-shape would have a higher crest factor and a more trapezoidal wave-shape would have a lower crest factor.

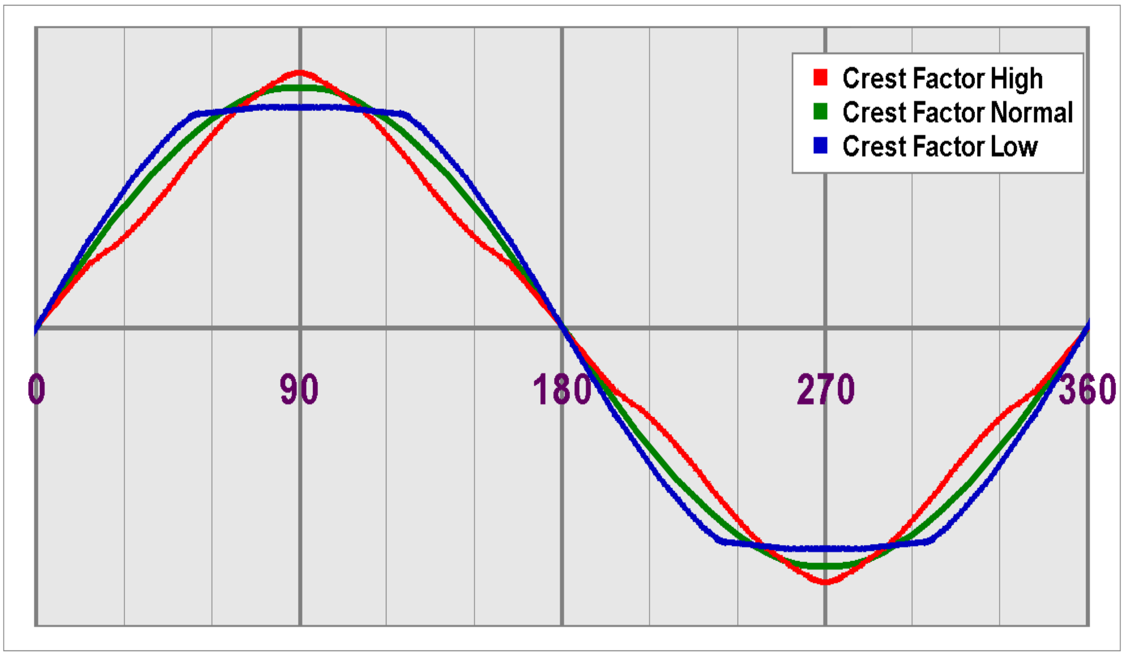


Figure 11. Crest Factor.

6.2. K-FACTOR

Power companies and transformers manufacturers use the K Factor rating as it establishes a link between harmonics and the losses they cause. A transformer must be capable of handling the harmonic levels in the expected load current so manufacturers specify a de-rating or K-Factor rating for the transformer, which must be higher than the K-Factor rating of the current in the circuit and where:

$K = \sum_{1}^{\infty} Ih(pu)^2 \times h$ Where Ih(pu) is the magnitude per unit, i.e. $Ih(pu) = \frac{Ih}{I_{RMS}}$

K-Factor rating of a transformer leads to an increase in its size and so increases costs. Typical values for K-Factor in transformers are 1, 4, 7, 13, 20, 40 and 50.

6.3. POWER FACTOR

Power Factor is a complex concept so it is best to draw a power tetrahedron to help visualise the complex relationships between; real (true or active) power (P) measured in Watts (W); apparent power (S) measured in volt-amps (VA); reactive power (Q) measured in reactive volt-amps (var); and distortion power (D) measured in distortion volt-amps (vad). Note that the three axes: P, D and Q are at right angles to one another. (See **Figure 12**)

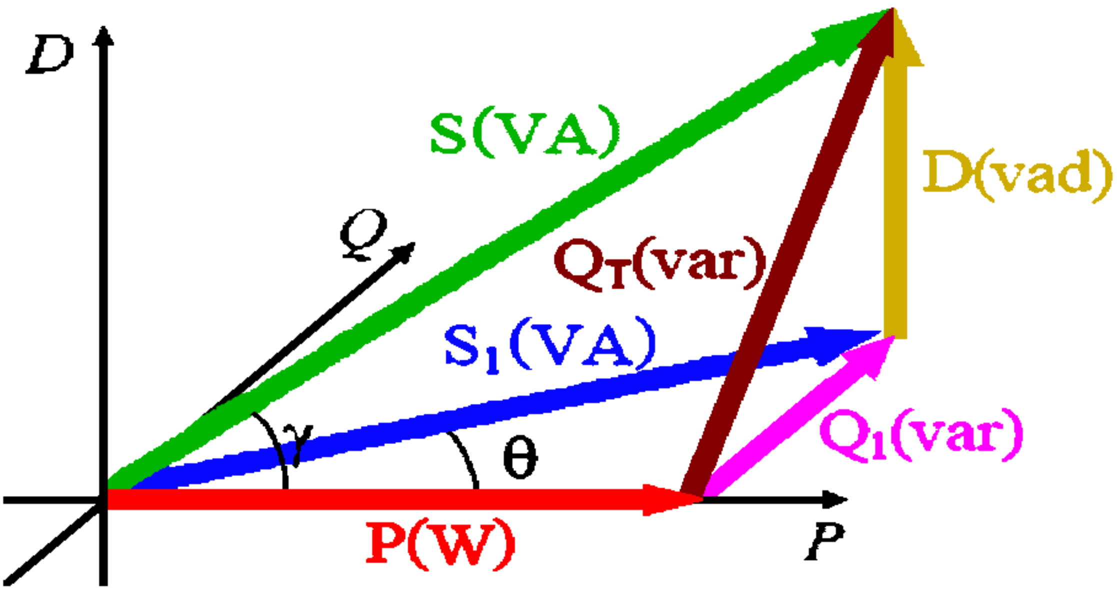


Figure 12. Power Tetrahedron.

In **Figure 12** above:

$Q_T = \sqrt{S^2 - P^2}$ and $Q_1 = V_1 I_1 sin\theta$ where subscript 1 refers to the fundamental.

D is the reactive power carried by the harmonics, where $D = \sqrt{Q_T^{\ 2} - Q_1^2}$

6.3.1. Displacement Power Factor

Power factor (PF) is one measure of power quality and its most commonly used form is more correctly called displacement power factor (**PF$_D$**) which is the ratio of the true power (**P**) consumed by the load and the power (in the fundamental) (**S$_1$**) provided by the utility. This is also the Cosine of the phase angle **θ** between the voltage and current supplied to the load and is shown graphically in **Figure 13.**

$$\mathrm{PF_D} = \frac{P}{S_1} = \cos\theta$$

However, using Displacement Power Factor as a measure of power quality is acceptable only if both the voltage and current waveforms are purely sinusoidal, and will lead to errors and inaccuracies if applied to measurements on any modern non-linear electronic equipment which produce non sinusoidal waveforms.

6.3.2. True Power Factor

A better measure of power quality when non-linear loads are present is the True Power Factor **(PF$_T$)** which is the ratio of True Power **(P)** measured in Watts (W) as measured with a true Wattmeter, to the Apparent Power (**S)** measured in volt-amps (VA) which is the product of the rms voltage and rms current.

$$\mathrm{PF_T} = \frac{P}{S} = \cos\gamma$$

This definition takes into account both the phase shift and the wave-shape distortion.

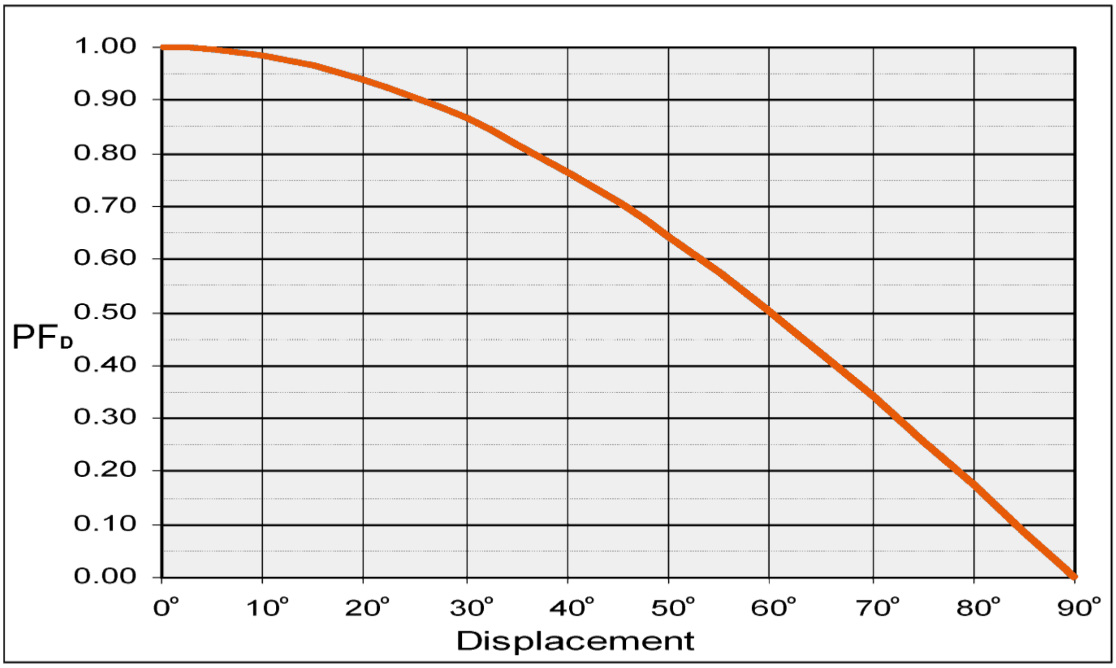


Figure 13. Relationship between Angular Displacement and Displacement Power Factor.

6.3.3. Displacement Power Factor V True Power Factor

The true power factor cannot be higher than the displacement power factor.

The relationship between displacement power factor and true power factor is:

True Power Factor = Distortion Power Factor x Displacement Power Factor.

Where the distortion power factor is the ratio of the current in the fundamental to the total current. In more detail, Watson [12], shows that:

$$\text{True Power Factor} = \frac{\text{Active power}}{\text{Total Apparent Power}}$$

$$= \frac{\frac{1}{T}\int_0^T v.i dt}{V_{RMS} I_{RMS}} = \frac{\sum_{n=1}^{N} V_n I_n \cos(\theta_n)}{V_{RMS} I_{RMS}}$$

$$\approx \frac{V_1 I_1 \cos(\theta_1)}{V_1 I_{RMS}} = \frac{I_1}{I_{RMS}} \times \cos(\theta_1)$$

$$= \text{Distortion Factor} \times \ \text{PF}_D$$

6.3.4. Utility's Power Factor Requirements

Utilities require the Power Factor of loads to be greater than 0.95, as a Power Factor of much less than 1 implies that the Utility has to supply more current to the user for a given amount of power used, thus incurring more line **(I^2R)** losses. Utilities then also need larger wattage equipment to carry this extra current.

For example, if the power factor of a load that uses 20 kW of real power is only 0.5, that implies that 40 kVA of power needs to be supplied to the load even though only 20kW of real power is actually used by the load. So the supply capacity (transformers, cables, switchgear, etc.) must be double the size they could be if the power factor of the load was 1. As a result, industry is usually charged a penalty for a poor power factor by KVA of maximum demand.

Industry tends to have large inductive induction motors, which give a 'lagging' power factor. Capacitive loads have the opposite effect giving a 'leading' power factor, which can compensate for the usual Inductive load. Some industrial sites use large banks of capacitors just for correcting the power factor to near one, which saves on utility penalty charges. Domestic users are currently not individually penalised for not meeting the minimum power factor and harmonic requirements because they are not monitored. However, with the introduction of 'smart' meters, the utilities now have the means of measuring each user's power factor and harmonic distortion, so domestic users may in future be charged for not meeting the required limits.

6.4. Harmonic Distortion

6.4.1. Harmonics

A pure sine wave consists of only one frequency, the fundamental, which is 50 Hz at 230 Volts rms in the case of the New Zealand residential power distribution network. Harmonics are multiples of the fundamental frequency and **Figure 14** shows the typical harmonics produced by some common domestic loads.

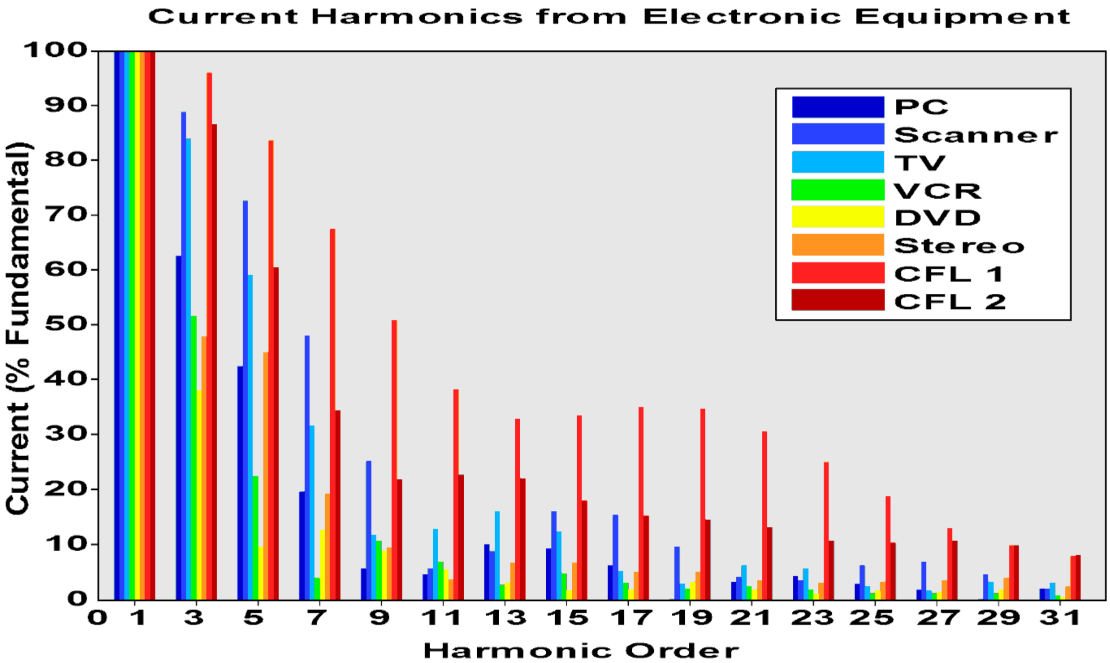


Figure 14. Typical harmonics from some common domestic loads [3].

6.4.2. Total Harmonic Distortion

Total Harmonic Distortion **(THD)** is one of the most widely used indices for describing power quality issues in distribution networks as it considers the contributions of every individual harmonic component.

THD is the ratio of the sum of all the rms values of the harmonic components to the fundamental component. THD is usually expressed as a percentage: **%THDv** for voltage; and **%THDi** for current.

$$THD_I(\%) = \frac{\sqrt{\sum_{2}^{\infty} Ih^2}}{I_1} \times 100$$

Thus, a THD greater than 100% means that there is more energy in the harmonics than in the fundamental. A pure sinusoidal waveform will have a THD = Zero.

6.4.3. Effects of Harmonics

Harmonics cause losses within the power distribution network, so it is inefficient to have harmonics present within the network. Harmonic currents in the network also have significant effects on distribution equipment and can lead to increased costs due to maintenance, failures, or device de-rating.

Transformer stray losses are proportional to the square of the current amplitude and related to the frequency by an exponential growth factor of not more than 0.8, while their winding eddy current losses are proportional to the square of the amplitude and the square of the frequency. This causes overheating well before reaching the transformer's rated 50 Hz load limit. So, when harmonics are present, transformers may need to be de-rated **[13]**.

Capacitors in power factor correction units may fail when harmonics are present as capacitors offer low impedance to harmonics, causing them to overheat. Harmonics also cause additional heating in cables due to skin and proximity effects, which increase with frequency; and dielectric breakdown, may also occur. Harmonics may cause abnormal time delay in switching circuitry and malfunctions in electronically controlled systems. False tripping may occur due to greater sensitivity of circuits to high frequency currents. Harmonics can interfere with ripple control and other power line carrier systems and cause unstable and unpredictable operation of zero crossing detectors. Other more subtle effects may lead to costly and unnecessary maintenance or equipment replacement, as the real culprit, harmonic distortion, is difficult to identify. Customers may also experience problems from distorted voltage waveforms and harmonic currents, which may overheat or damage motors, cause light flicker, and interfere with communication and other equipment. Some power meters may also give incorrect readings when harmonics are present.

In a 4-wire 3-phase system the fundamental currents in the neutral will always add up to zero. However, the third harmonic of each phase is always in phase with those of the other two phases, so rather than cancel, these third harmonic currents are additive and may lead to serious neutral loading problems. For example: if a three phase system has a 100 Amp load and each phase has 30% third harmonic, the harmonic current flowing through the neutral will be 3x30% of 100, or 90 Amps at three times the fundamental frequency which is 150 Hz for a 50 Hz system. As a result, a neutral of at least double the capacity required for a linear load is required for non-linear loads. Due to the high frequency of harmonics and skin effect, the current flows on the outer surface of the conductor; so to minimize neutral impedance, it is therefore also preferable to use several conductors in parallel for the neutral, rather than using a single neutral conductor.

7. NEW ZEALAND RESIDENTIAL POWER NETWORK

7.1. CHARACTERISTICS OF NZ RESIDENTIAL NETWORK

The New Zealand residential power distribution network is a network of high voltage transmission lines operated by Transpower. The Network is made up of AC lines at voltages between 66 kV and 220 kV and includes a High Voltage Direct Current (HVDC) Link which runs from Benmore in the South Island to Haywards, just north of Wellington in the North Island [21].

The HVDC Link carries up to 1 GW from the South Island to the North Island and up to 0.6 GW in the opposite direction. The link is split into two halves:

Pole 1 uses old mercury arc valve technology and contains about 500kg of Mercury and was temporary "stood down" in 2007, it has however still been used since then. Pole 1 was partially decommissioned late in 2009, but half of Pole 1 was refurbished and is still in use today. [11].

Pole 2 uses modern thyristor power electronics.

(**Pole 3** which uses similar technology to pole 2, is currently under construction and is intended to start replace Pole 1 from late 2012 with final project expected to be completed probably in 2014 [11].)

7.2. POWER QUALITY OF NZ RESIDENTIAL POWER NETWORK

In New Zealand, unlike other countries, the transmission lines are un-transposed and our distribution network has long distances between the main generators and the main loads because of the "spread out" nature of settlements in New Zealand. For the New Zealand HVDC link, the Haywards/Wellington region remains a weak system with a low Short Circuit Ratio (SCR) [11]. The old 1960s mercury arc valve technology of Pole 1 injects a large amount of harmonic distortion into the New Zealand residential power distribution network. The exact level of this 'background' harmonic distortion is not known however. The mercury arc valve could also fail at any moment with catastrophic effect costing probably billions to clean up. All of this creates a “weaker” distribution network within New Zealand where both the voltage and the current waveforms deviate markedly from true sine, as shown in **Figure 15.** This deviation indicates the lower power quality expected within a distribution network having higher impedance than found in most first world power distribution networks. The power quality of weak networks is sensitive to non-linear loads so energy saving initiatives encouraging non-linear loads result in lowering the power quality in such networks [2].

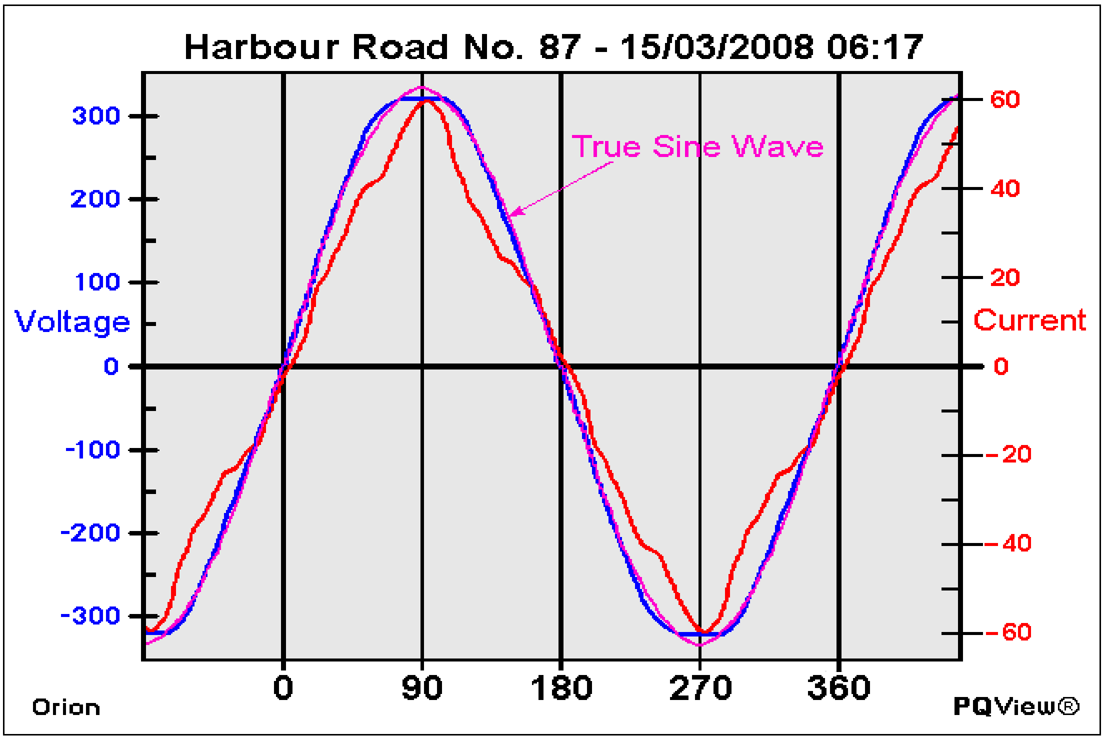


Figure 15. Voltage and Current waveforms at a typical New Zealand distribution transformer [22].

Utilities require users to keep their harmonics within the NZECP 36 limits [7], but in **Figure 16** the red bars show that the total harmonic distortion (THD) within in a typical residential distribution transformer peaks at 4.65% which is very near to the upper limit of 5% as specified in the New Zealand Electrical Code of Practice [10] and called up by Electricity Regulations 1997 [8] and now called up by Electricity (Safety) Regulations (2010) [9]. Recent local research indicates that non-linear loads have a current waveform that is rich in harmonics which distorts the voltage waveform of the residential power distribution network even further. The impact of the harmonics generated by the widespread adoption of non-linear loads is concerning as it is diverse and subtle and there is little recent research available on this topic.

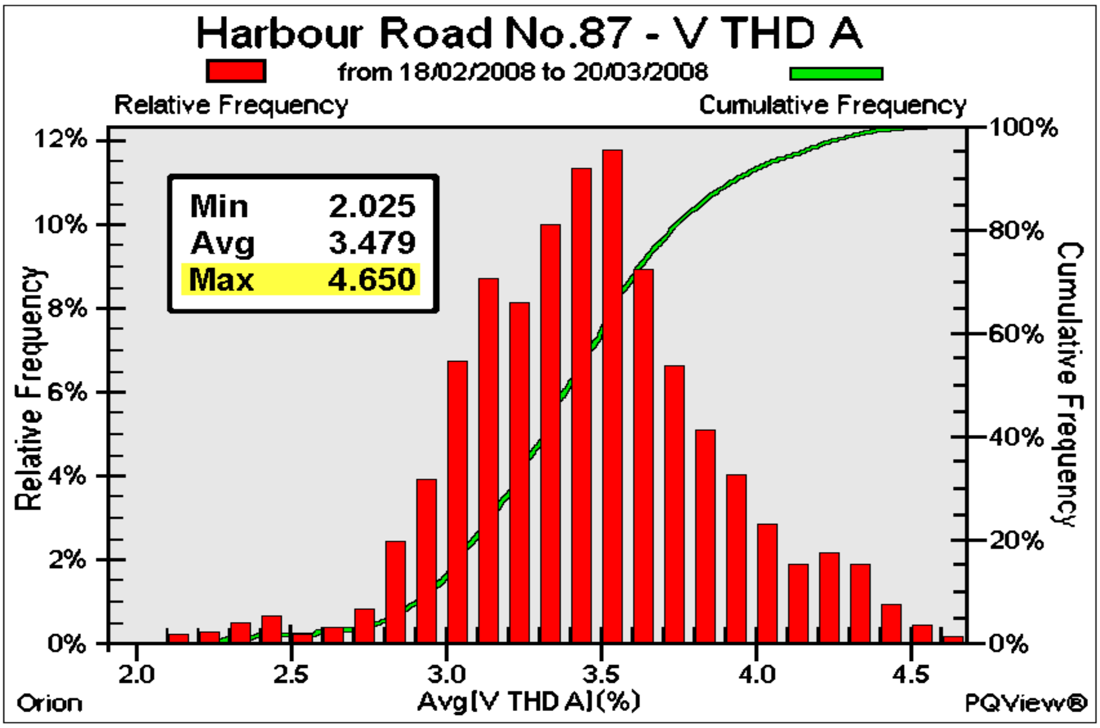


Figure 16. Actual %THDv at typical residential distribution transformer shows that the maximum level is 4.65% [22].

7.3. Drivers of Move to Non-linear Loads

Recently there has been a global move away from linear resistive loads towards non-linear loads. Linear resistive loads produce no adverse effects on the power quality of the low voltage residential power distribution network. These loads are generally relatively large and have a stabilizing effect on the network as, being resistive, they have a power factor of, or near, Unity. Currently however, almost all of the viable alternatives to replace these linear loads are non-linear, and have a negative effect on the power quality of the already degraded New Zealand residential power distribution network [1].

Referring to **Figure 15,** Stephen Hirsch, Control & Protection Systems Development Manager of Orion, explains that it is getting harder to find linear loads in homes and that the distorted peaky current waveforms in **Figure 15** are probably the result of a large number of non-linear loads, such as inverter heat pumps, TVs, PCs etc. as the voltage waveform shows the typical flat top caused by such non-linear loads [2].

There is a growing proliferation of high reliability, low cost non-linear electronic products such as: Computer games, televisions, video and audio equipment, multimedia devices and computers; heating ventilation and air conditioning equipment with variable speed motor drives; white goods and other appliances; food preparation and cooking products such as microwave ovens; modern lighting products such as compact fluorescent lamps (CFLs), fluorescent lamps with electronic ballasts, and LED lighting; chargers for cell phones, cameras etc.; and other power conversion devices that operate a variety of modern consumer products.

The drivers that have resulted in this proliferation are a direct result of the availability of low cost switch mode devices and control circuitry as well as the benefits that such technology can bring to end users such as lower operating costs, smaller size, weight reduction and improved performance **[23]**.

Other important drivers are the government led energy efficiency campaigns intended to reduce pollution from fossil fuel generation of electricity through reduced generation of electricity.

8. NON-LINEAR LOAD CHARACTERISTICS & EFFECTS

Line companies are becoming concerned, as the power quality of the New Zealand residential power distribution network is decreasing and residential load characteristics in New Zealand are indicating decreased power quality that may increase total harmonic distortion to over the 5% New Zealand limit **[2]**.

For example, compact fluorescent lamps (CFLs) draw about 75% less current than the older incandescent technology they replace and boast a longer lifespan. However, their integrated ballasts, which ensure their correct and efficient operation, in their most common design form, dramatically distort the waveform of the current drawn, introducing considerable harmonic distortion into the residential power distribution network. These CFLs are characterised by a low power factor and high harmonic distortion, and the widespread introduction of these and similar devices will lead to a further decrease in the power quality of the residential power distribution network.

The electronic front ends of modern non-linear loads make them more efficient than linear loads, but they decrease the power quality of the network by introducing considerable harmonic distortion. Non-linear loads also incur greater line losses and require larger power distribution equipment **[2]**.

Most modern devices have a simple non-linear rectifier front end as shown in **Figure 17**. This circuit is used to convert the suppled AC voltage into the DC voltage which is necessary to power most modern electronic appliances.

Unfortunately non-linear front ends are used in a wide range of household appliances such as TVs, stereos, PCs, microwave, compact fluorescent lamps (CFL), LED lighting, and all types of chargers (for cell phones, cameras etc).

The level of harmonic distortion caused by these devices is a direct function of the AC to DC converter design and as market forces increase pressure to cut costs, this results in simpler converter circuits with the lowest component count being the most common design used in almost all household appliances **[12]**.

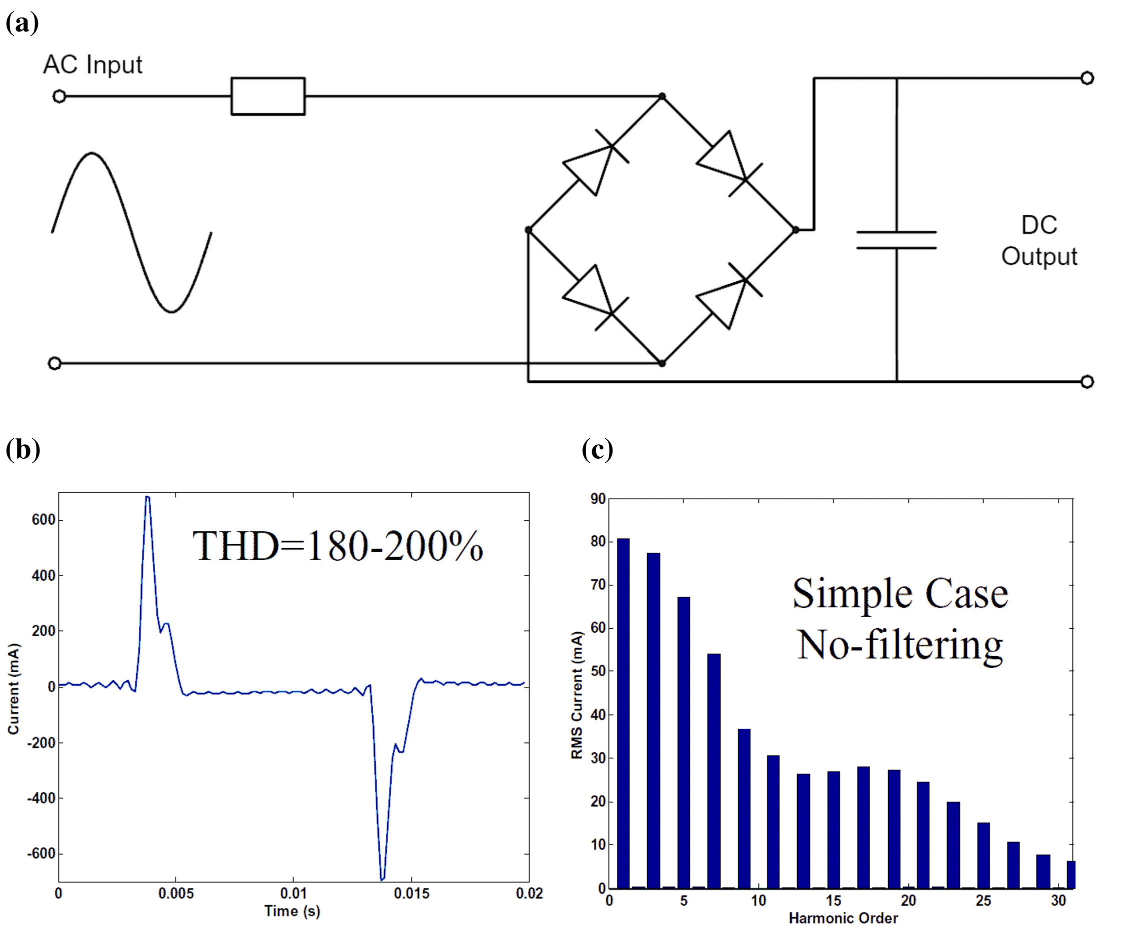


Figure 17. (a) AC/DC converter with no filtering, (b) current w-form, (c) very high harmonic distortion [12].

A simple way of increasing the converters power-factor and reducing the harmonic content of the input current waveform is the use of passive filtering. **Figure 18** shows a simple inductive/capacitive filter which, while it does reduce the harmonic content of the input current waveform does not eliminate it, leaving the harmonic distortion high enough to cause a problem, especially if used in devices installed in multiple quantities as their harmonic content may add.

Obviously, the more extensive the filtering is the better the AC current waveform, but the higher the cost. The advantage of this passive LC filtering technique is its simplicity and ease of implementation. However, the major drawback is the physical size and weight, which makes it unattractive due to the limited space and inherent power loss **[12]**.

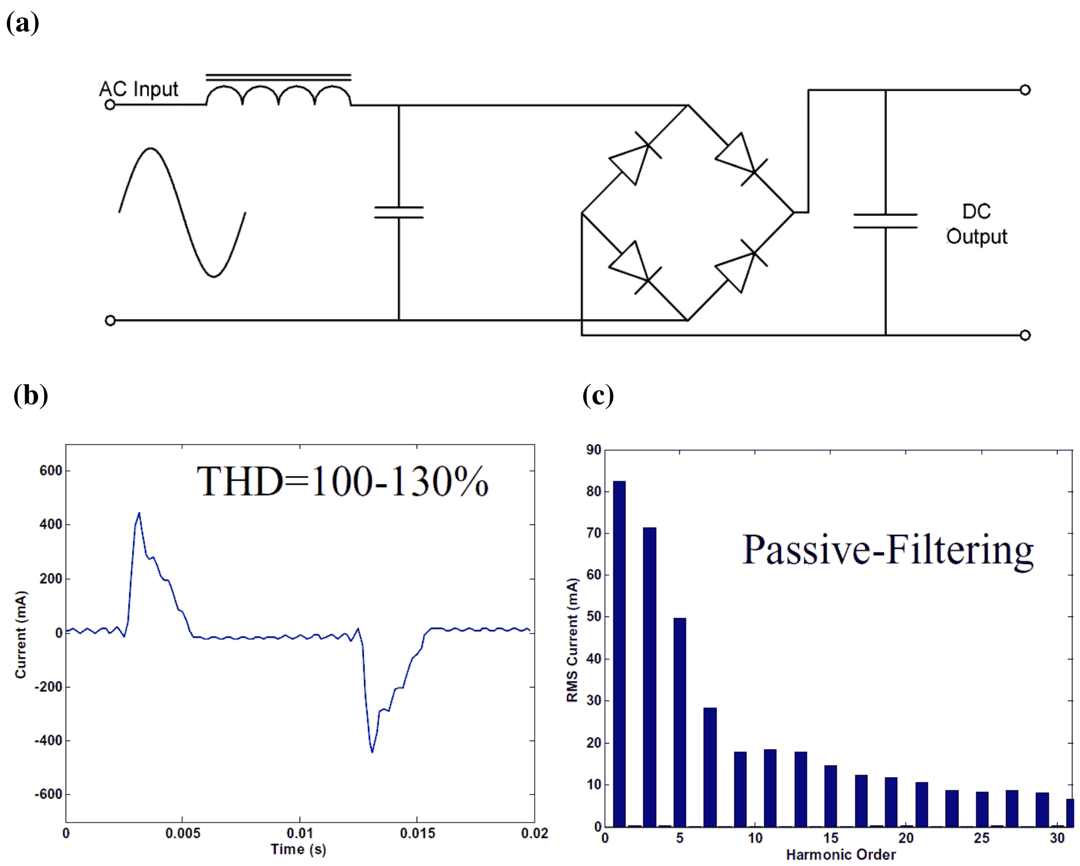


Figure 18. (a) AC/DC converter with passive filter, (b) current w-form, (c) high harmonic distortion [12].

Figure 19 shows a more complex "valley fill" front end which further reduces the harmonic distortion to acceptable levels, but does add more complication and cost to the final product. In this circuit, the filter capacitor following the diode rectifier split into two different capacitors C1 and C2, which are alternately charged and discharged using three diodes D1,2&3. However, this circuit contains large DC voltage ripple, which produces lamp power and luminous flux fluctuation. As a result, it will reduce the lamp's lifetime. An improved valley-fill circuit adds two more capacitors as a voltage doubler, which helps to extend the input current conducting angles. This is a cost effective way of improving power factor as well as reducing the harmonic current levels [12].

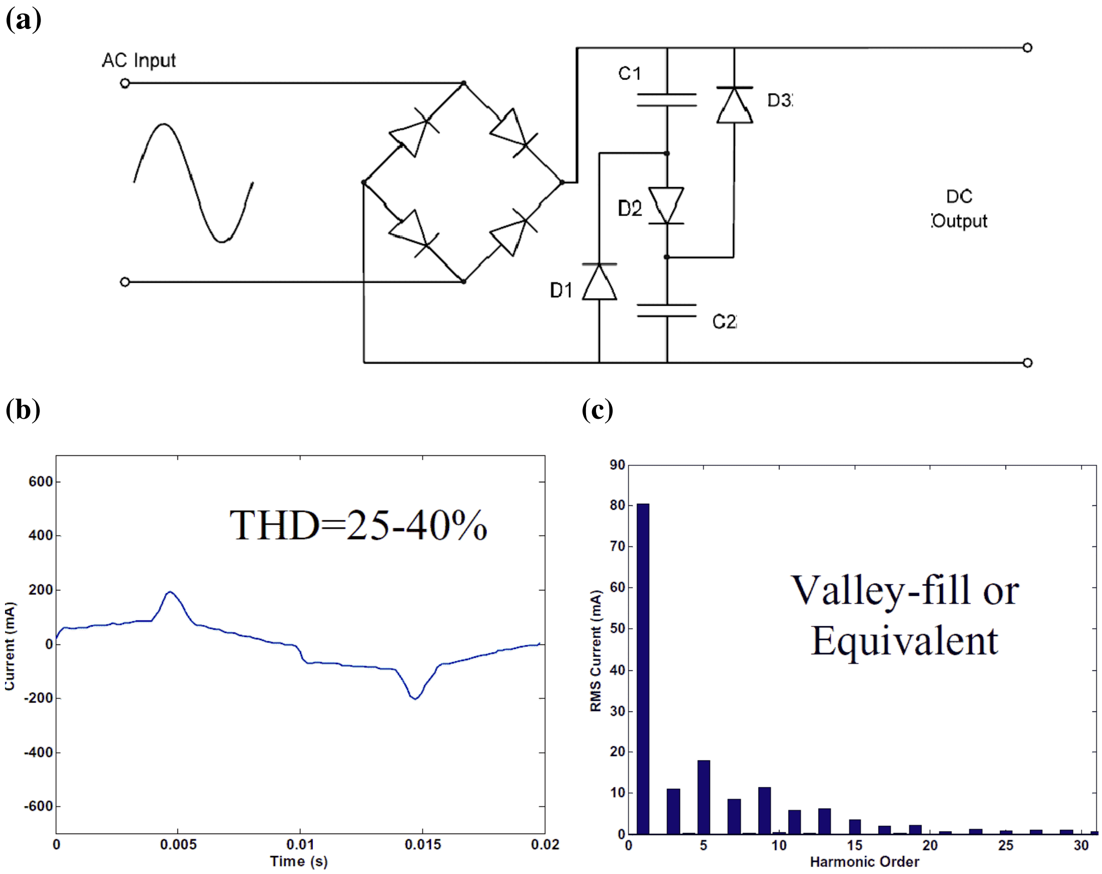


Figure 19. (a) AC/DC converter with valley-fill, (b) current w-form, (c) low harmonic distortion [12].

Figure 20 shows the most complex solution, which uses an active "power factor correction" circuit, which almost entirely eliminates the harmonic distortion, but adds the most complication and cost to the final product. Active filtering is the most advanced and costly method to obtain high power-factor electronic ballast. A high frequency switch is normally used to correct the input power factor. In this circuit, unlike the inductor/capacitor in **Figure 18,** the inductor/capacitor in **Figure 20** forms part of a boost circuit where the current is controlled by the power factor control drive such that the overall current drawn by the circuit is sinusoidal and so eliminating current spikes. Dedicated IC chips are manufactured for controlling the switch in these active power-factor controlled ballasts. Due to mass production, this increased cost is only significant in very low cost devices such as CFLs **[12]**.

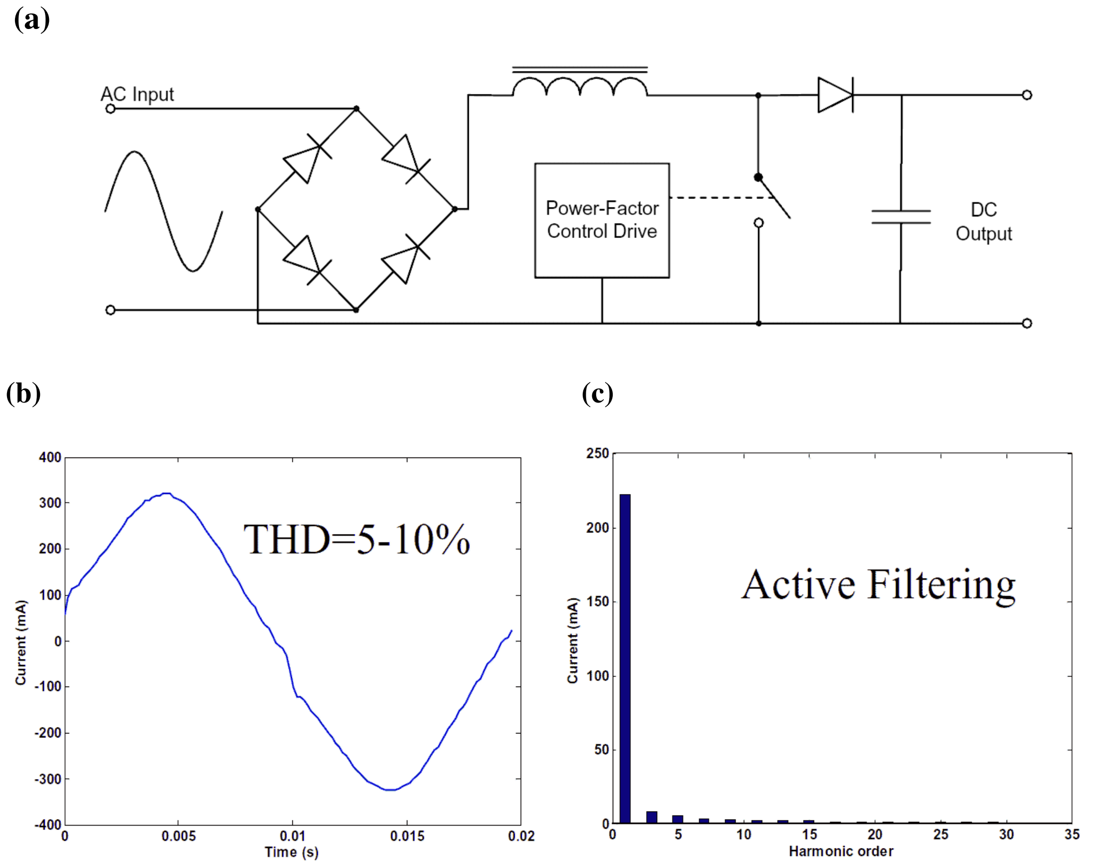


Figure 20. (a) AC/DC converter with active filter, (b) current w-form, (c) almost zero harmonic distortion [12].

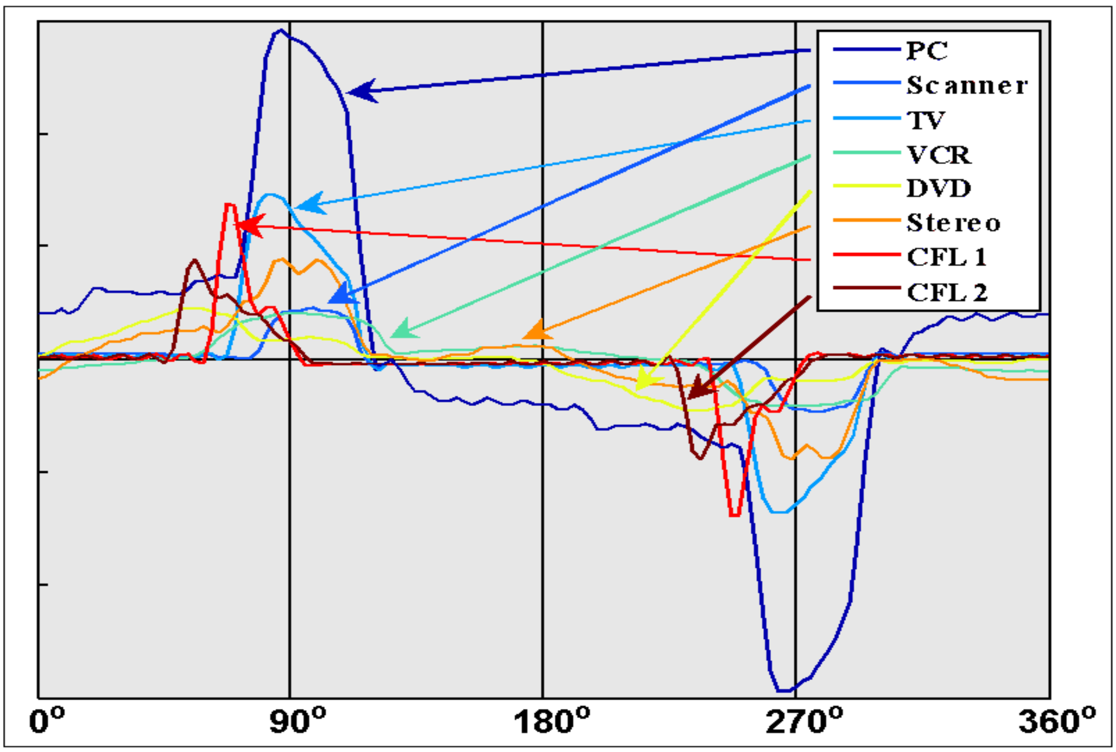


Figure 21. Actual current waveform of a variety of common non-linear domestic loads [3].

Figure 21 & 22 show actual current waveforms and harmonic distortion levels for a variety of domestic non-linear loads, which illustrate the effects of the great variety of conversion techniques used in practice.

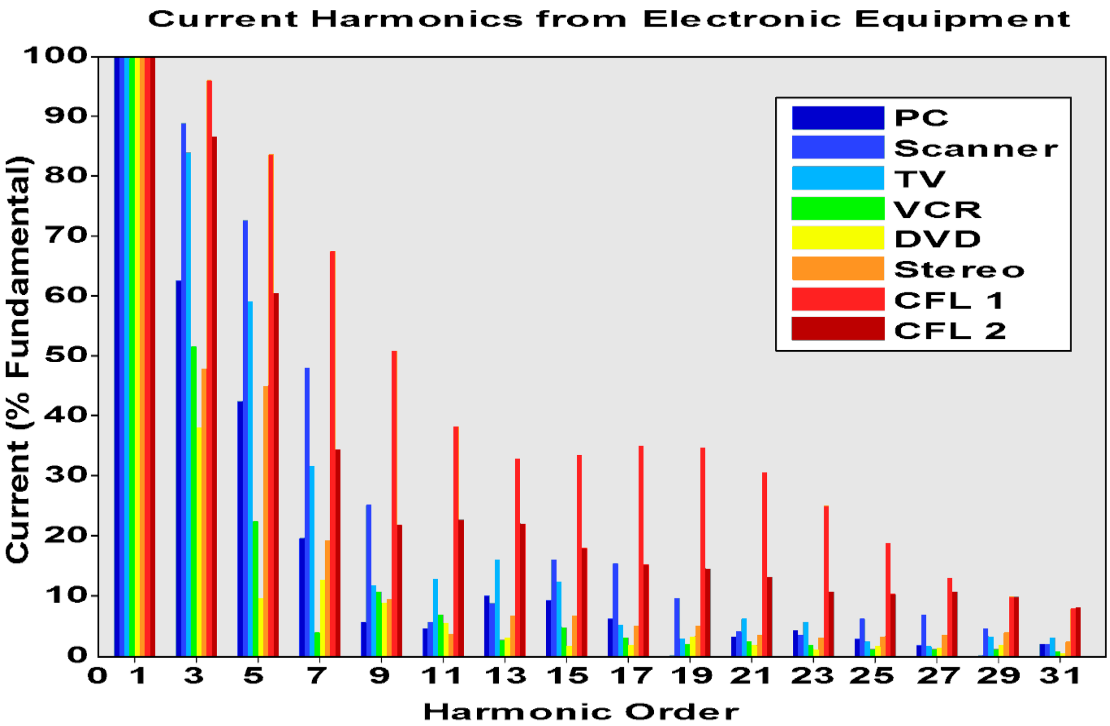
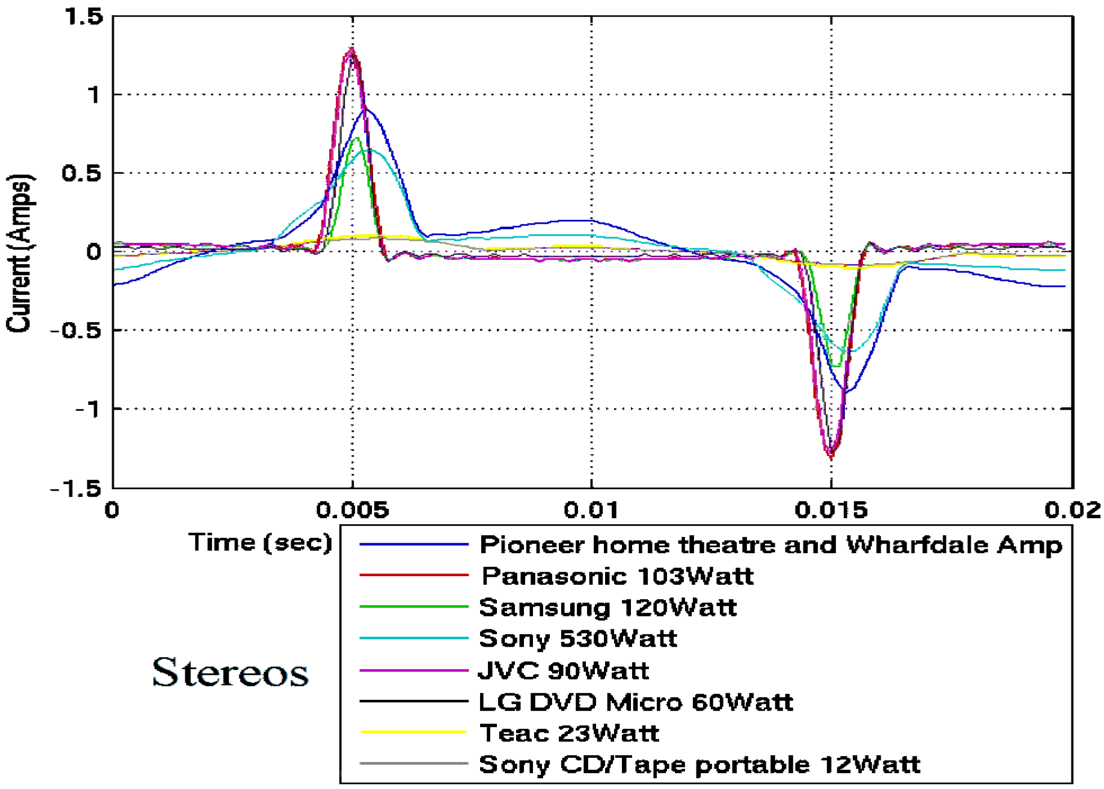


Figure 22. Typical harmonics from some common non-linear domestic loads [3].

8.1. Multiple Non-linear Load Interaction

As non-linear loads interact, harmonics increase as more loads come on, because harmonics from even identical devices can just as easily reduce or cancel as increase. So even though the frequencies and amplitudes of the harmonics may be the same for both devices, the phases of even the same harmonics in the multiple devices may well be different so a different combined harmonic profile than expected may result. This then implies that even small non-linear loads can have a large impact on the network if their harmonic currents have similar phases.

Recent testing was conducted on a wide range of common modern domestic household appliances by Hardie & Watson [20] and their relative current waveforms and associated harmonics are shown in **Figures 23 to 27**. These tests indicate that most of these modern devices are non-linear and contribute considerable harmonic distortion into the already ‘noisy’ New Zealand power distribution network.



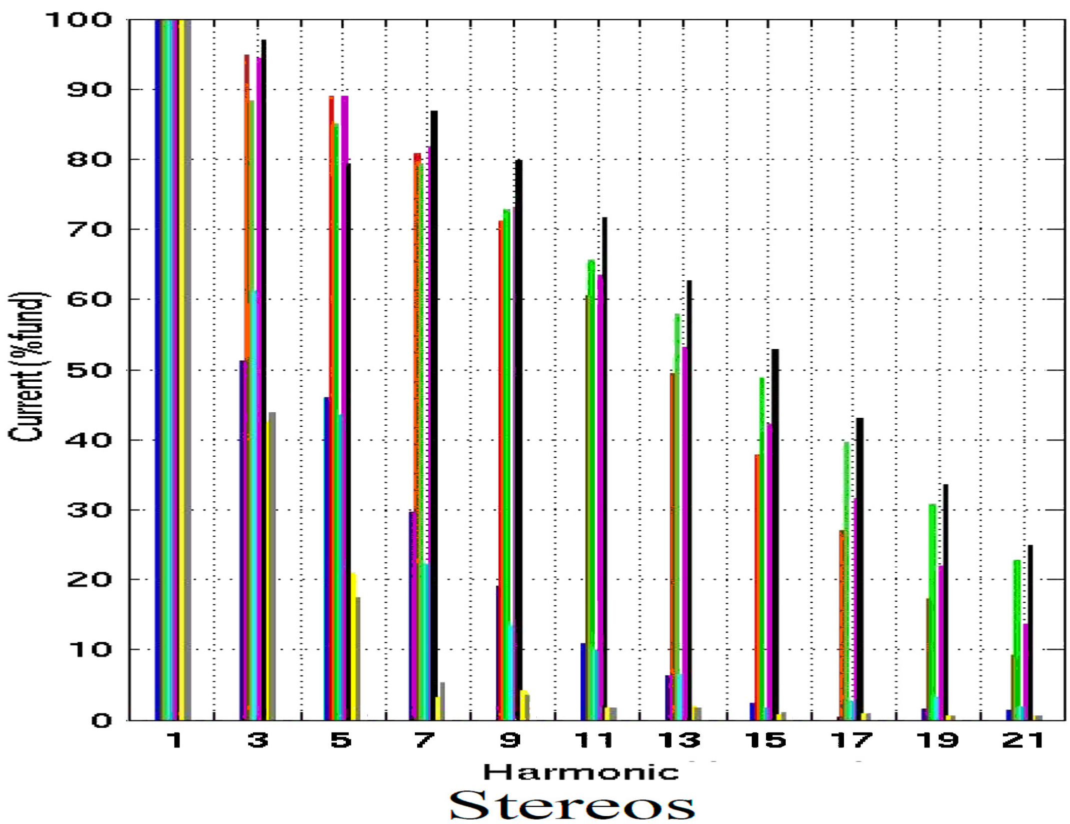


Figure 23. Stereos Relative Current Waveforms and Associated Harmonics [20].

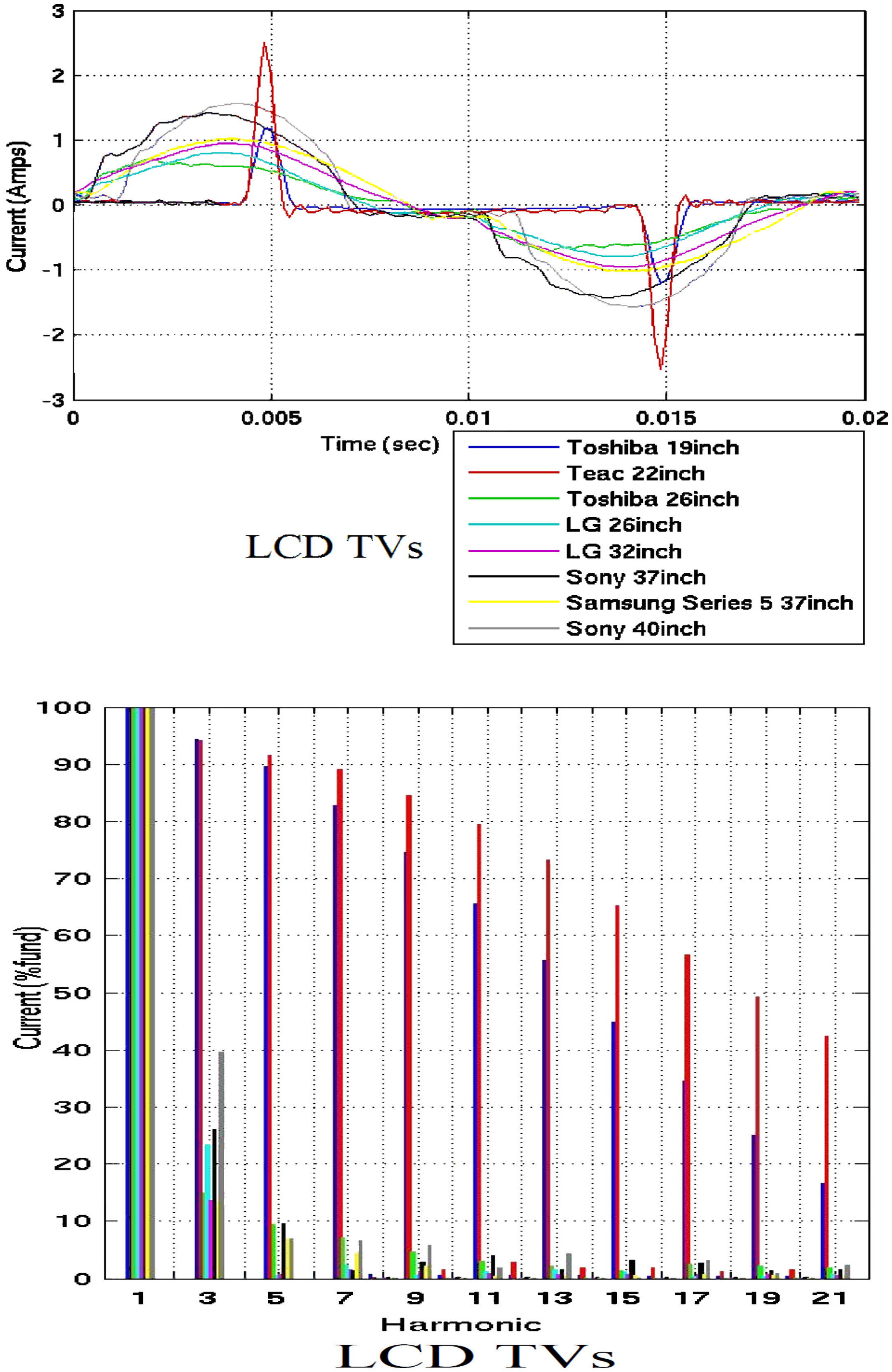
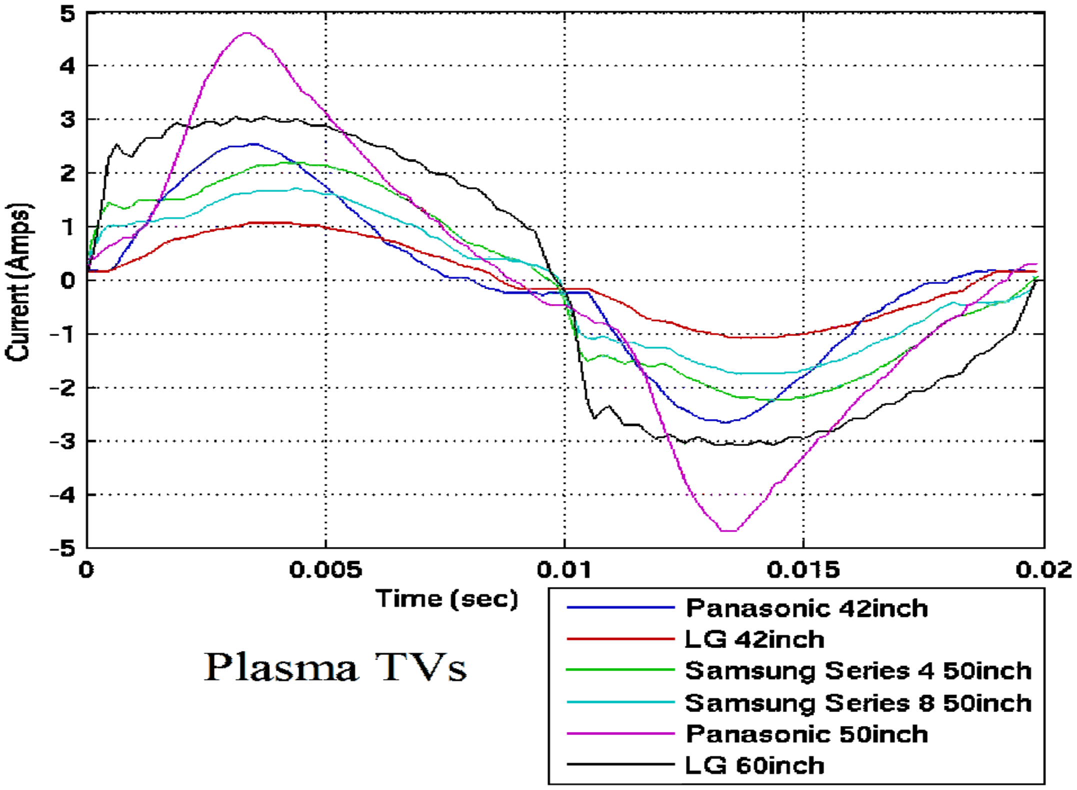


Figure 24. LCD TVs Relative Current Waveforms and Associated Harmonics [20].



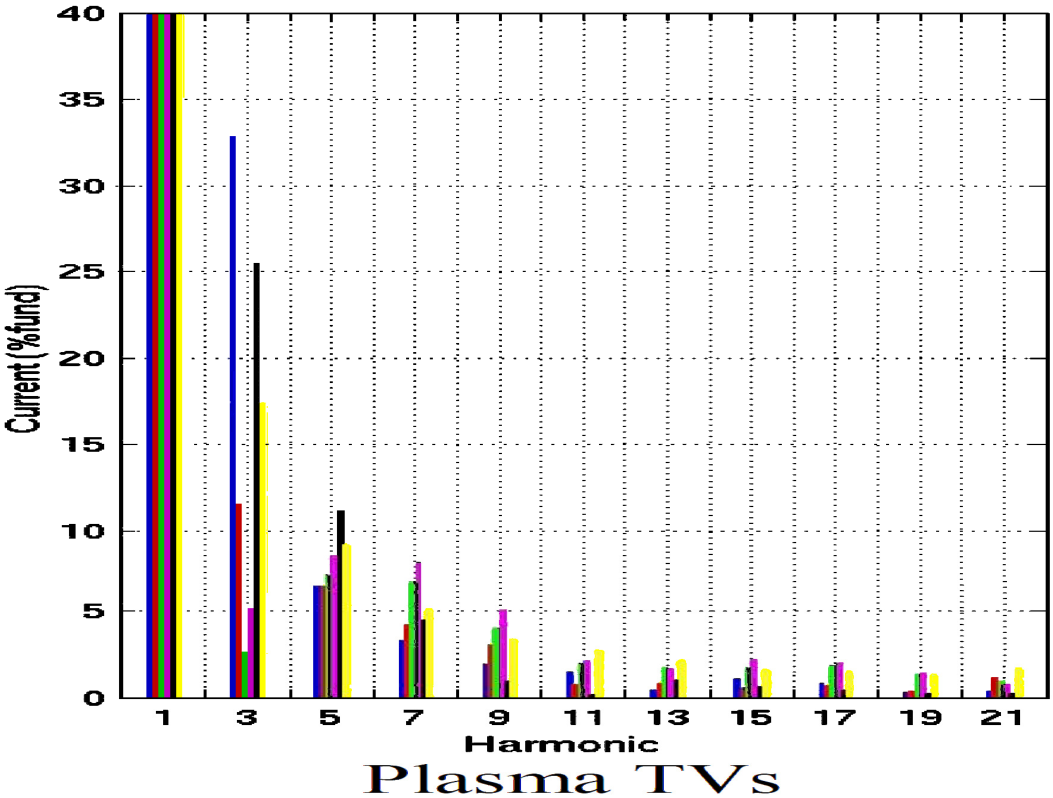
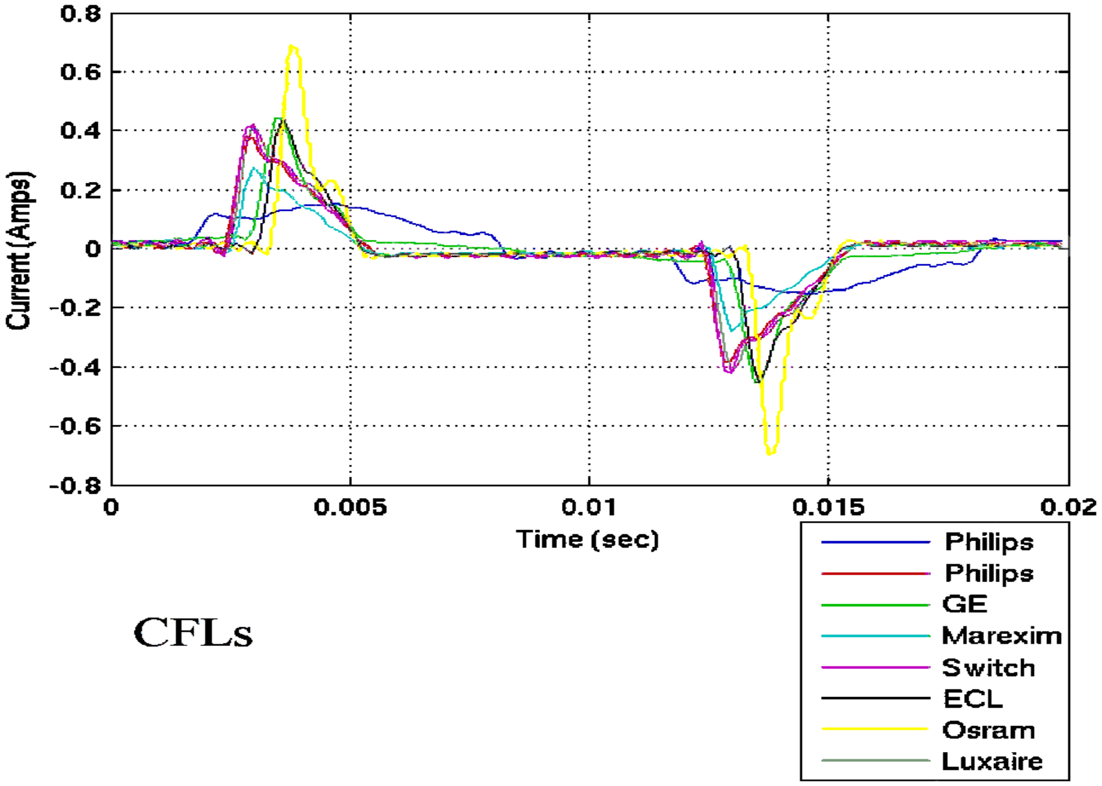


Figure 25. Plasma TVs Relative Current Waveforms and Associated Harmonics [20].



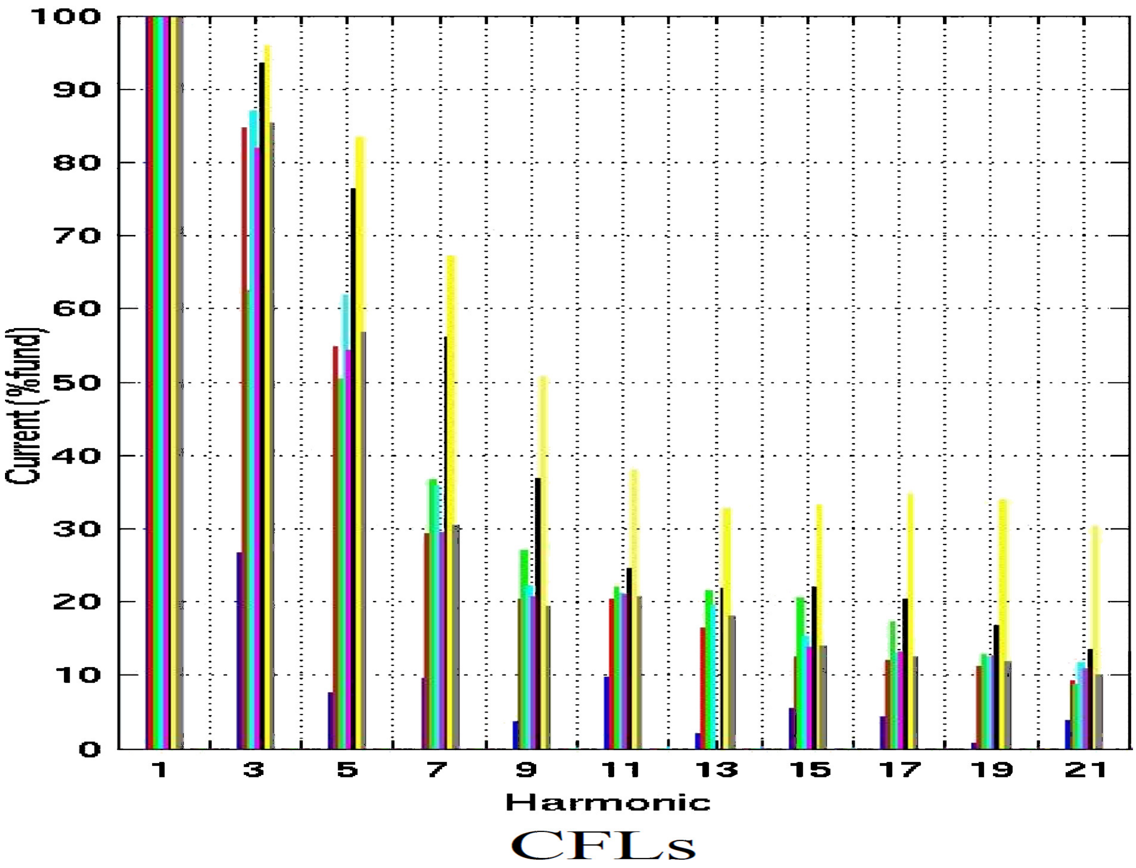


Figure 26. CFLs Relative Current Waveforms and Associated Harmonics [20].

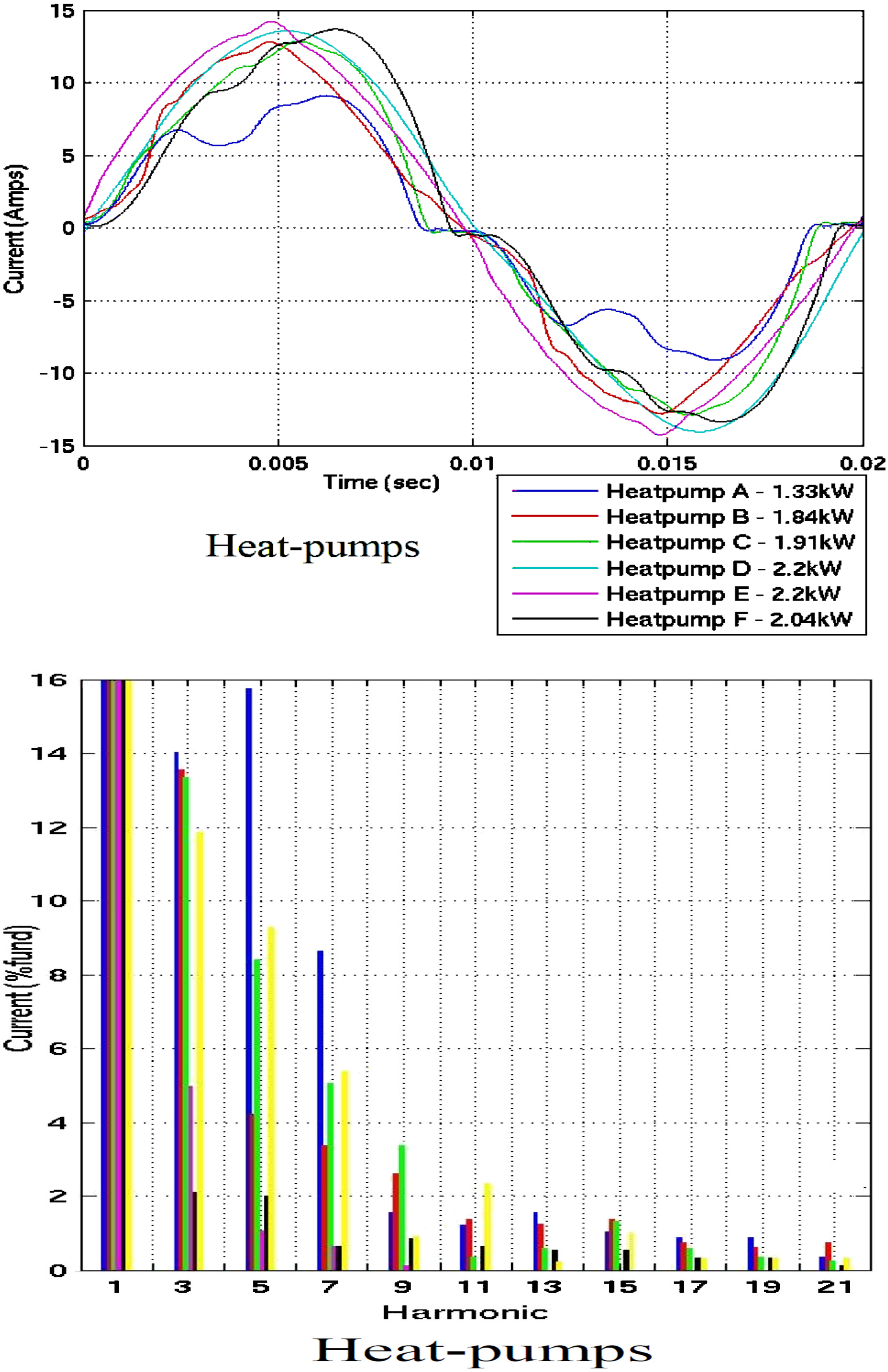


Figure 27. Heat Pumps Relative Current Waveforms and Associated Harmonics [20].

Further measurement of the relative phase angle of their harmonics indicates that, although some products may have harmonics at phase angles that tend to cancel, many have harmonics with very similar phase angles meaning that their harmonics will add. This then becomes a serious issue when multiple such devices with similar harmonic profiles and with similar phase angles are installed together in one location. When these products are installed in multiple quantities, their combined disturbing effect is compounded and much worse than that of a single higher powered device that has to meet a much more stringent harmonic requirement. This is again further compounded if the harmonics produced in these multiple small devices have similar phases. The 3rd and 5th harmonic current magnitudes and phase angles of the non-linear loads tested by Hardie & Watson [20] are shown in **Figure 28**.

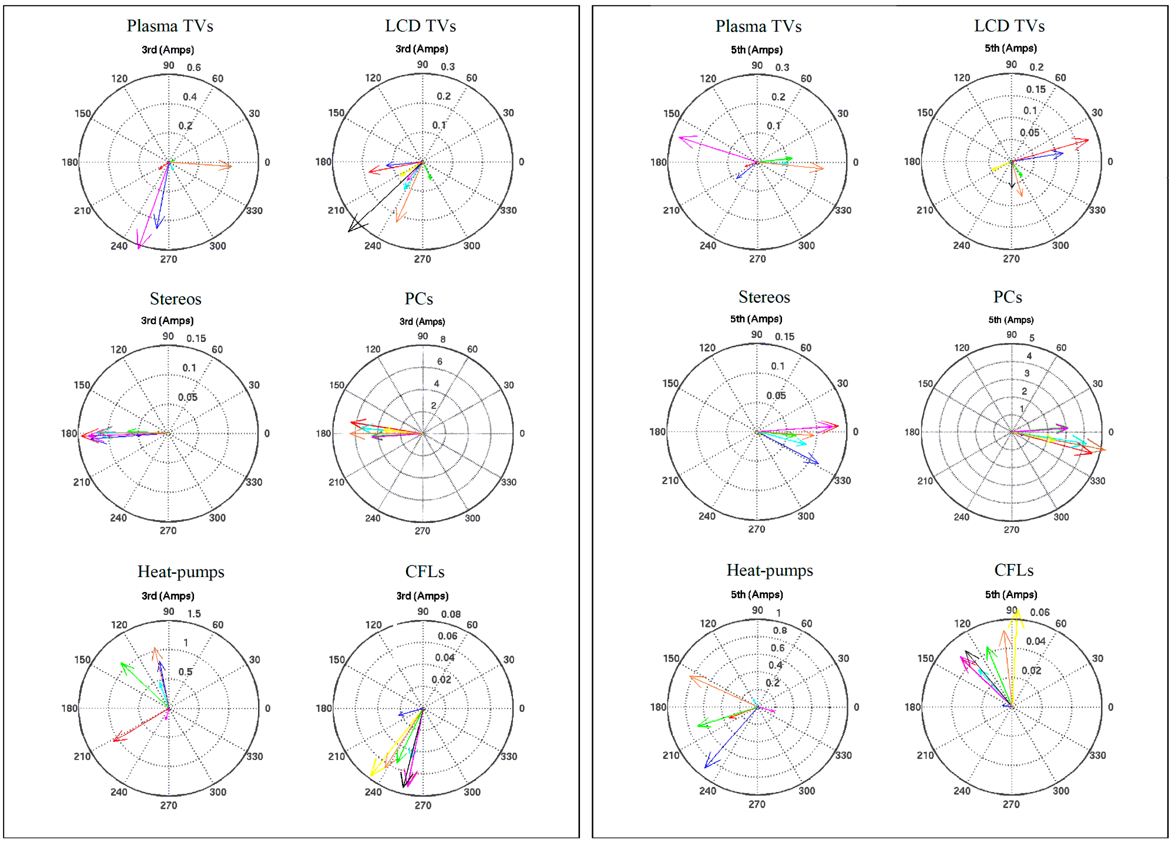


Figure 28. Harmonic Amplitude and Phase Angle of a Range of Products [20].

Plasma TVs show a large variation in harmonic phase angles but variations in harmonic phase angles for LCD TVs are much lower. This then results in harmonics generated from different LCD TVs reinforcing each other rather than cancelling, and thus multiple LCD TVs may cause higher voltage distortions at their Points of Common Coupling (PCC) than multiple Plasma TVs. All of the stereos tested had very limited harmonic phase angle diversity and both the third and fifth harmonic angles of the stereos align with the PCs harmonic phase angles, which implies that stereos and PCs will enhance each other's harmonic distortion when used together.

Lower power appliances are generally of less concern to the network, and so have a less stringent compliance requirement. However, where their harmonic angles align when operating multiples of these devices together, harmonic reinforcement may result in the introduction of significant harmonic distortion into the power distribution network.

Most modern heat pumps use Variable Speed Drives (VSD), which increases efficiency, but, as they are non-linear, they are a considerable source of harmonic distortion. The heat-pump harmonics also increase significantly when operating at lower power levels. There is also low diversity between heat-pumps for their 3rd and 5th harmonics phase angles as can be seen in **Figure 28** [20].

CFL lamps are low power (usually less than 25 Watts,) but there is low harmonic phase angle diversity between almost all CFLs. While the low power of these lamps means that the absolute magnitude of the harmonic currents of a single lamp is relatively small, unlike other appliances, each residential home may have a dozen or so CFLs on at the same time. Home owners are also likely to purchase lamps of the same brand and this will cause a harmonic profile with almost zero magnitude or phase diversity. But even if a wide range of brands are purchased, strong harmonic reinforcement is most likely to occur. The impact that all these harmonics have on a power distribution network depends on the power of the appliance that is the source of the harmonics, and the current wave-shape that appliance draws [20].

Harmonic phase angle diversity is relevant when multiple appliances are operating simultaneously, creating either reinforcement or cancellation of harmonic magnitudes. **Figure 29** shows a comparison of the appliances tested by Hardie & Watson [20]. The black line in **Figure 29** shows the Harmonic Limit according to AS/NZS 61000.3.2 [17]. While CFLs and stereos have high current distortion, their low power and current magnitude limit their harmonic impact on the network. However as CFLs are usually installed in multiples, a more realistic comparison is shown for 10 CFLs.

The effect of very low harmonic angle diversity in CFLs suggests that multiple CFLs should be considered as a single high power CFL lamp with corresponding high harmonic current distortion which is of concern to the weak New Zealand power distribution network [20].

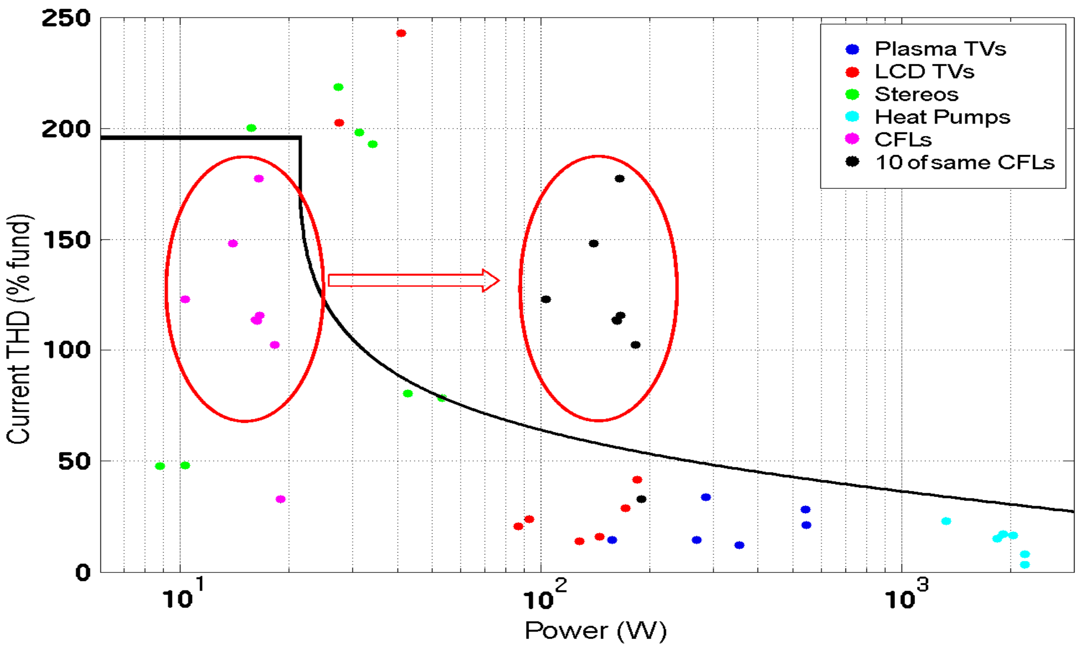


Figure 29. Comparison of current distortion between categories of appliance [20].

A set of 10 CFLs produce around 200W of Total Harmonic Distortion, which is as much as or more than the actual THD produced by a 1kW heat pump.

Hardie & Watson [20] state, “Scenarios were calculated for where 10 CFL bulbs were connected per house and where all appliances (including 10 CFLs per house) were connected. To keep the total feeder load approximately level in the various scenarios, the individual linear loads were set to 2.5kW for the first five scenarios, 1.5kW for the heat-pump scenario and 1kW for the scenario where all appliances were connected. Additionally for each scenario, calculations were made for modelled appliances with their measured harmonic angles and for where all appliances had no diversity, that is, all harmonic angles were set to zero. This reveals the reduction in harmonic voltage that multiple appliances will provide due to harmonic currents being partially out of phase resulting in their partial cancellation.”

Hardie & Watson [20] explained that, “The most significant, single appliance category harmonic voltage increases are due to multiple CFLs and to heat-pumps. This shows that CFL lamps are likely to be one of the highest sources of harmonics in New Zealand’s power distribution networks, especially as many heat-pumps are unlikely to be all running simultaneously for long periods, while multiple CFL bulbs are often switched on together for hours in the evenings. The effect of all appliances being simultaneously connected is to provide some more harmonic angle diversity between the categories of appliances and thus a much lower harmonic voltage is generated than what the scalar sum of the harmonic currents of all the appliances would create. For instance, the harmonic angle diversity of all appliances lowers the voltage THD from a possible 3.2% to an actual 1.2% at the top of the feeder." They continued by stating that, "In general, harmonic voltage levels at the end of the feeder were up to 50% larger. The effects of harmonic angle diversity were also reduced. This would be of concern for longer feeders. Harmonic voltage increases are likely in longer feeders in rural areas due to the higher line impedances." And they concluded with, "The range of appliances tested and measured shows that many of the loads being connected to the network today create moderately significant current harmonics. While the power of most of these devices is low, the large and increasing numbers of appliances with low harmonic angle diversity means that harmonic voltage levels are likely to rise in the future within LV and MV distribution networks. New non-linear appliances are now being sold which will replace present linear loads. For example, resistive water cylinder heaters may be swapped for water heat-pumps and domestic fridge/freezers are now being sold that use a VSD, instead of a direct on line compressor. These new appliances are likely to accentuate the harmonics issues."

8.2. MONITORING NON-LINEAR LOADS

To better understand the impact of non-linear loads on the power quality of the residential power network, broad long-term monitoring of domestic power quality needs to be conducted in order to build up a precise domestic load profile. This requires the monitoring of a large number and wide range of loads' individual characteristics and their hourly, daily, weekly monthly, seasonal and annual usage.

There are two main approaches to monitoring loads, Intrusive and Non-intrusive. Intrusive load monitoring involves attaching small measuring devices to each individual load and monitoring these devices remotely using many complex measuring devices which intrude on each load measured which makes this method prohibitively expensive. The other problem with intrusive load monitoring is that installation requires intrusion into the user's household.

Non-intrusive load monitoring involves one simple measuring device attached to a single point, usually the point of common coupling, the distribution board, which sends data to complex software for analysis and identification of each individual load and its current draw. This requires monitoring and sampling at very high rates, requiring complex fast software and large storage capacity. This method is popular as there is only one device making this method relatively simple and less expensive and it is becoming easier as more ‘smart loads’ which include chips to enable them to be interrogated and controlled via the mains are introduced within domestic loads. This then lead to the concept of ‘smart meters’ talking to ‘smart loads,’ leading to ‘smart homes,’ where not only the hot water unit is controlled by the energy provider, but also the other appliances, so a heat pump may be controlled to run at a maximum of 50% at a certain time of day and so on.

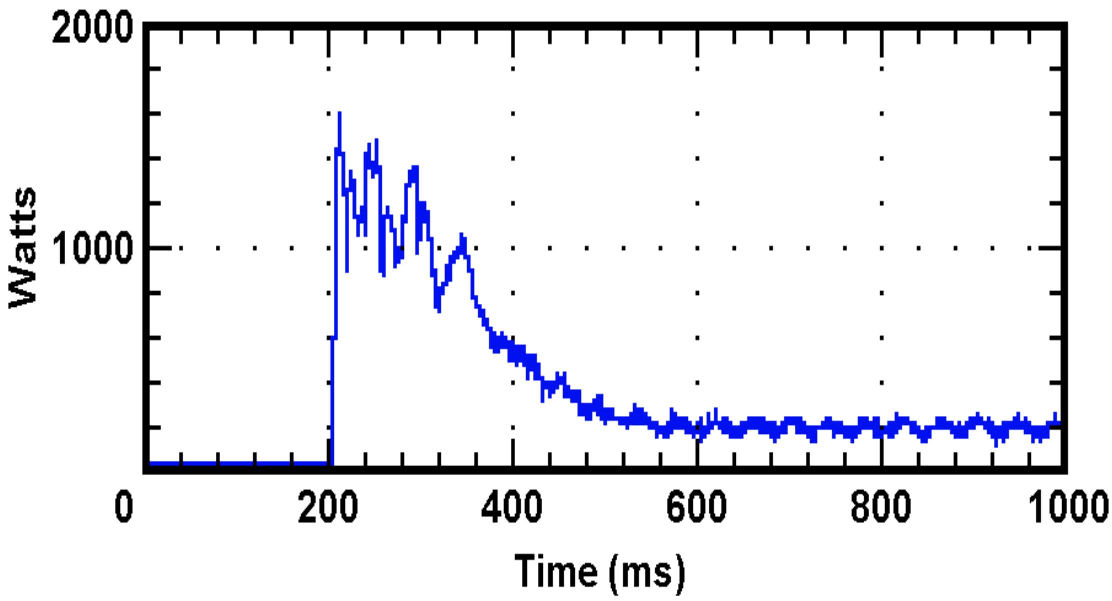


Figure 30. Turn on Transient Signal for a Motor.

In an application of non intrusive load monitoring the current is measured many times a second and a signature for each load is built up. It is then possible to recognize the transient signature of each load within the overall current signal and identify the loads that are on at any particular time and what state they are in. This is fairly straight forward and requires measurement at moderate data rates probably in the hundreds of Hz range. **Figure 30** shows a typical complex transient signal.

However, both the intrusive and non-intrusive methods are not cost effective when measuring user loads within the residential power distribution network so this research looked for other more cost effective methods.

A simple method is to measure the step changes in real power at the point of common coupling and in this way recognizing which load is on. But it is not possible to differentiate between loads by simply measuring step changes in real power as many domestic loads have the same real power.

Figure 31 shows five different loads of 30, 20, 50, 50 and 20 Watts respectively. (Colour coded for easy identification).

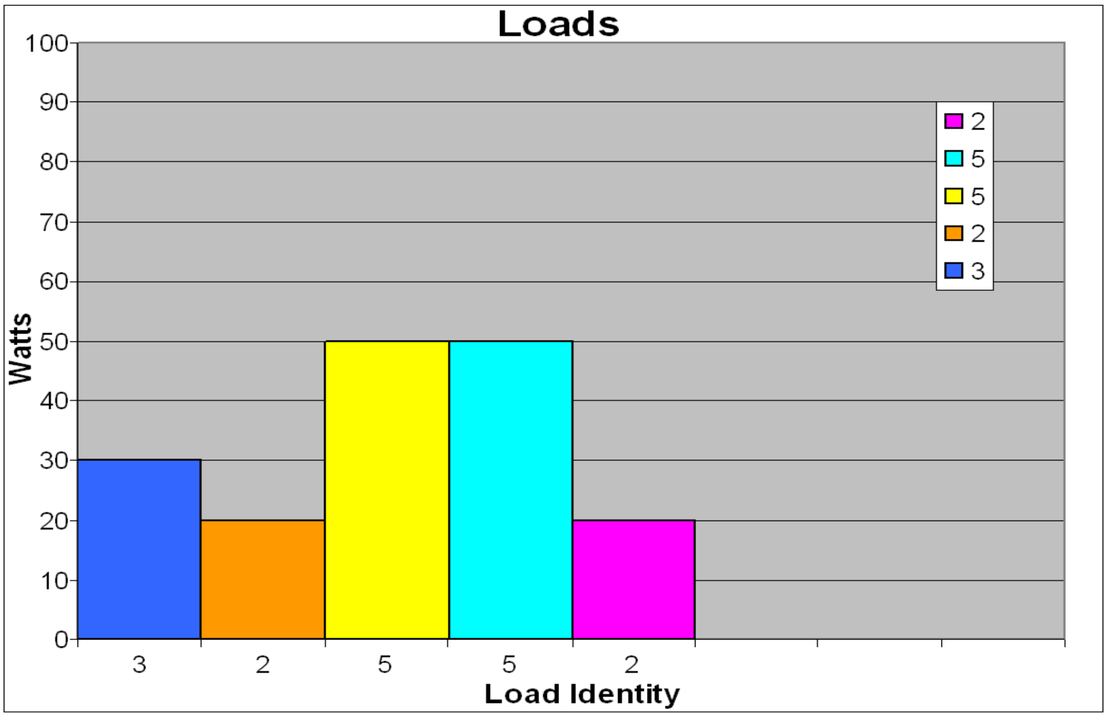


Figure 31. Loads of 30, 20, 50, 50 and 20 Watts.

Figure 32 gives a hypothetical daily load profile using these five loads, but it soon becomes obvious that while it is easy to see when the 30 Watt load comes on and off, it is not possible to differentiate between the two 50 Watt (yellow and pale blue) or between the two 20 Watt (orange and purple) loads.

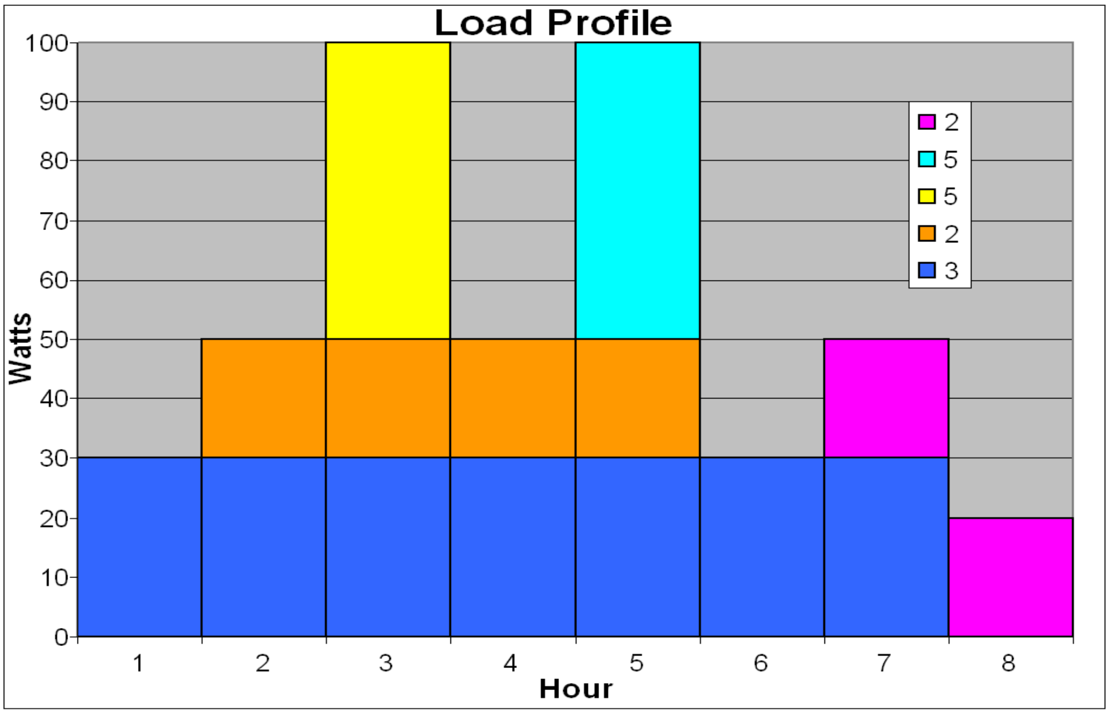


Figure 32. Daily Load Profile.

A slightly more advanced method is to measuring the step changes in real and reactive power and use these changes to create a signature for each load. Although this technique is common and has been developed commercially, it cannot differentiate between devices with similar real/reactive power signatures.

Figure 33 shows the same five different loads of 30, 20, 50, 50 and 20 Watts, but now their reactive power of 1, 1, 2, 3 and 1 VA have been included.

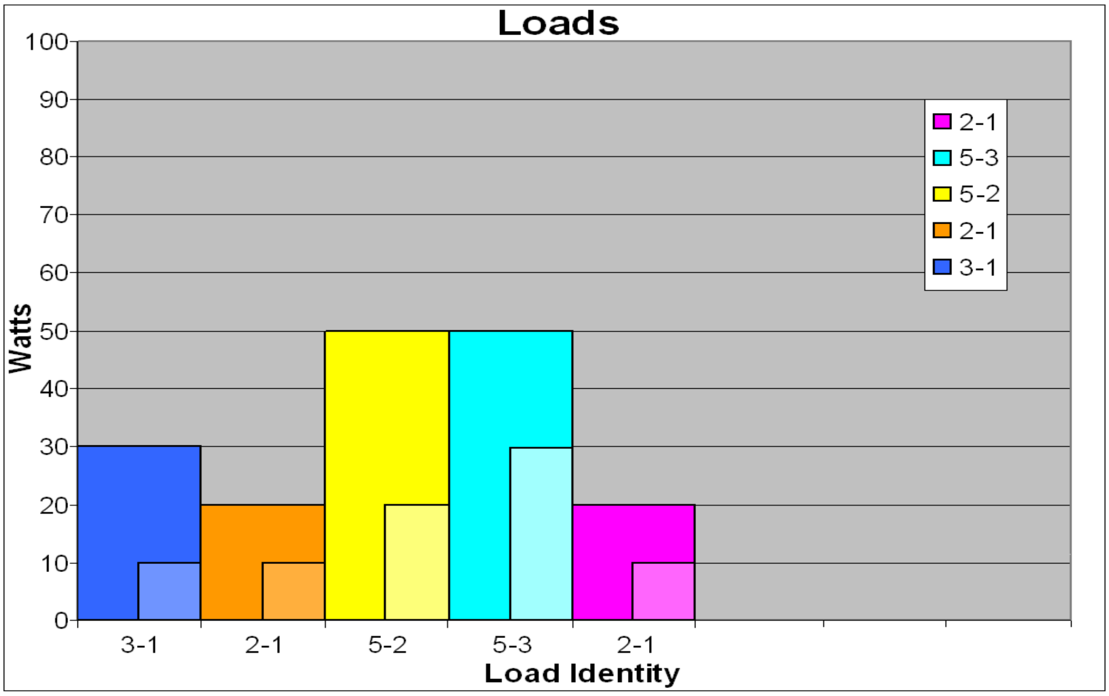


Figure 33. Loads of 30, 20, 50, 50 and 20 Watts.

Figure 34 gives a hypothetical daily load profile using the five loads although it is now easy to differentiate between the two 50 Watt loads, (yellow and pale blue) as they have different reactive powers, it is still not possible to differentiate between the two 20 Watt (orange and purple) loads as they both have the same reactive power.

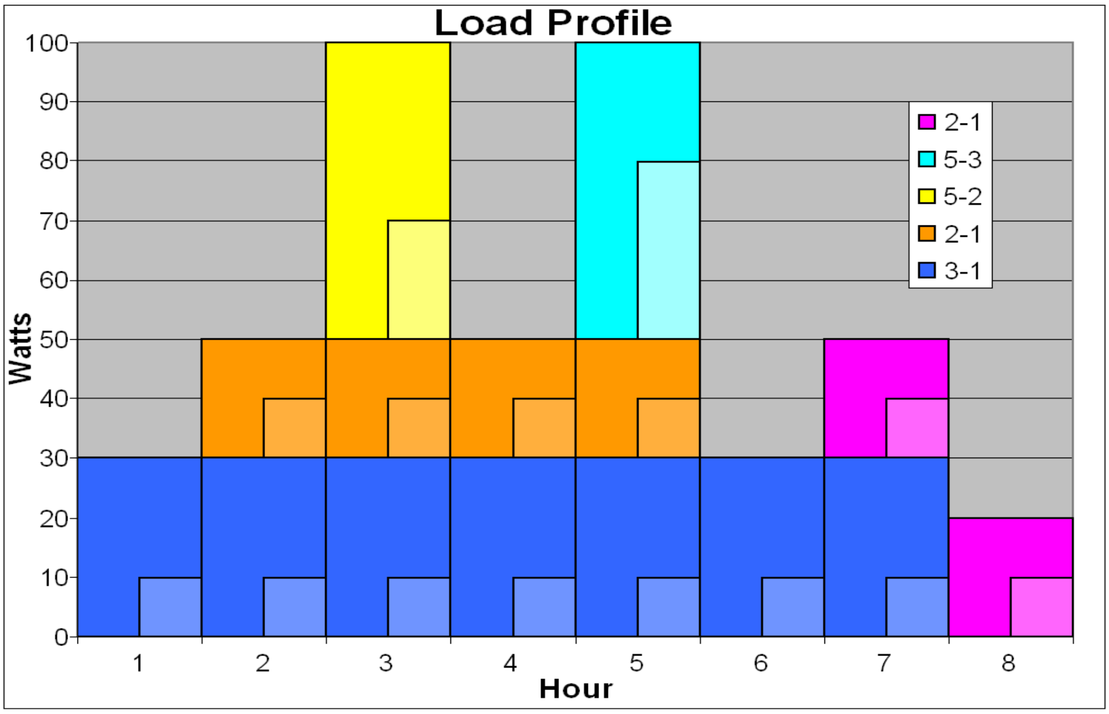


Figure 34. Daily Load Profile.

A simple real application of this method is to measure the changes in Real (P) and Reactive (Q) power at the distribution board. Changes are defined as steps between any two steady-level states, and a steady state is a period of time where the power usage remains relatively constant.

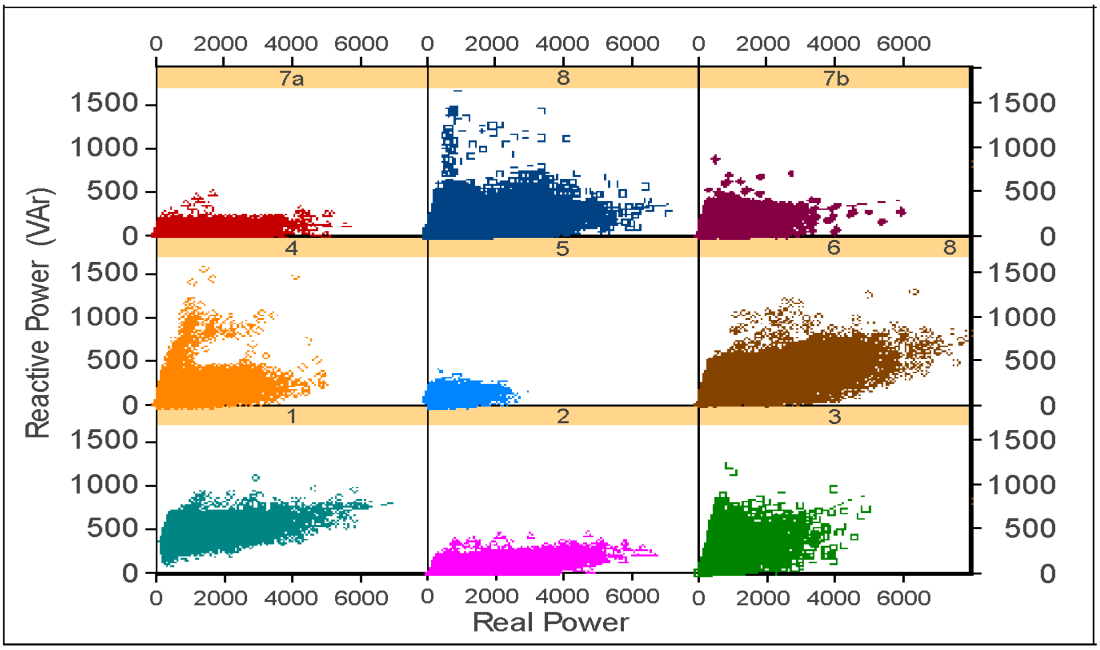


Figure 35. Daily Real (P) and Reactive (Q) power profiles of 9 typical homes [4].

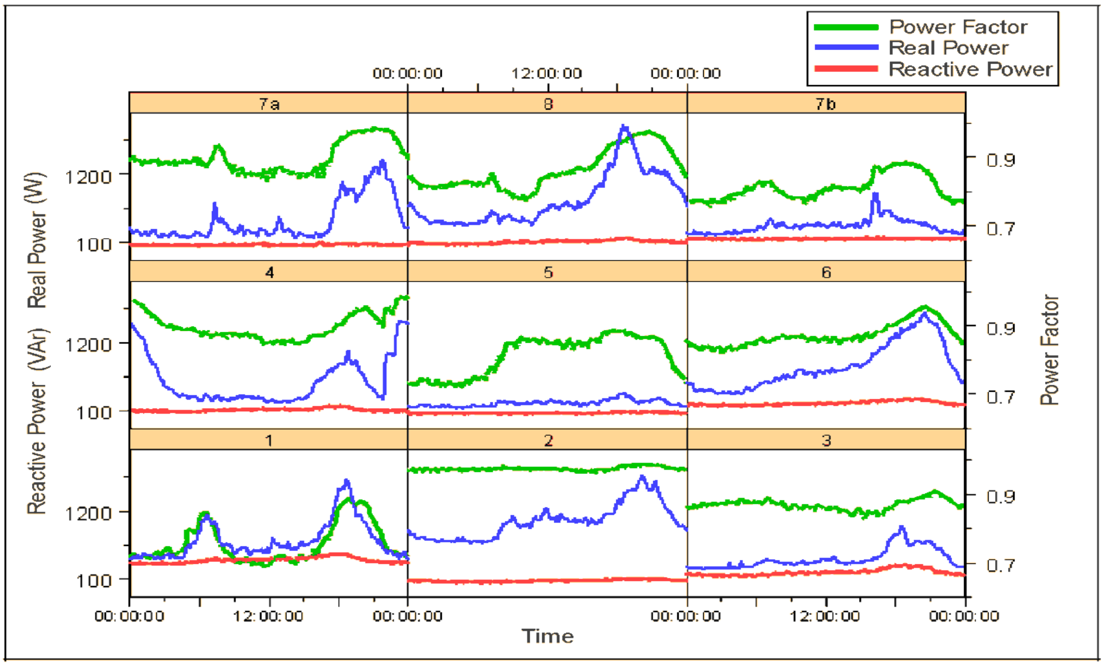


Figure 36. Actual Real (P) Reactive (Q) powers and Power Factor with respect to time over 24 Hrs for 9 typical homes [4].

Figure 35 shows the daily Real (P) and Reactive (Q) power profiles of 9 typical homes and Figure 36 shows the actual Real (P) Reactive (Q) powers and Power Factor with respect to time over 24 Hrs for 9 typical homes.

Using these points, a signature of changes can be created for each load and can be plotted on a PQ-plane. This approach is simple and has been developed commercially, but it still cannot differentiate between loads with similar PQ signatures.

The approach finally developed in this research for future implementation goes one step further, measuring not only the real and reactive power but also the harmonics. Measurement needs to be at a sampling rate approaching 10 kHz, and then analysed by software which makes it fairly easy to differentiate between an almost infinite range of similar load signatures.

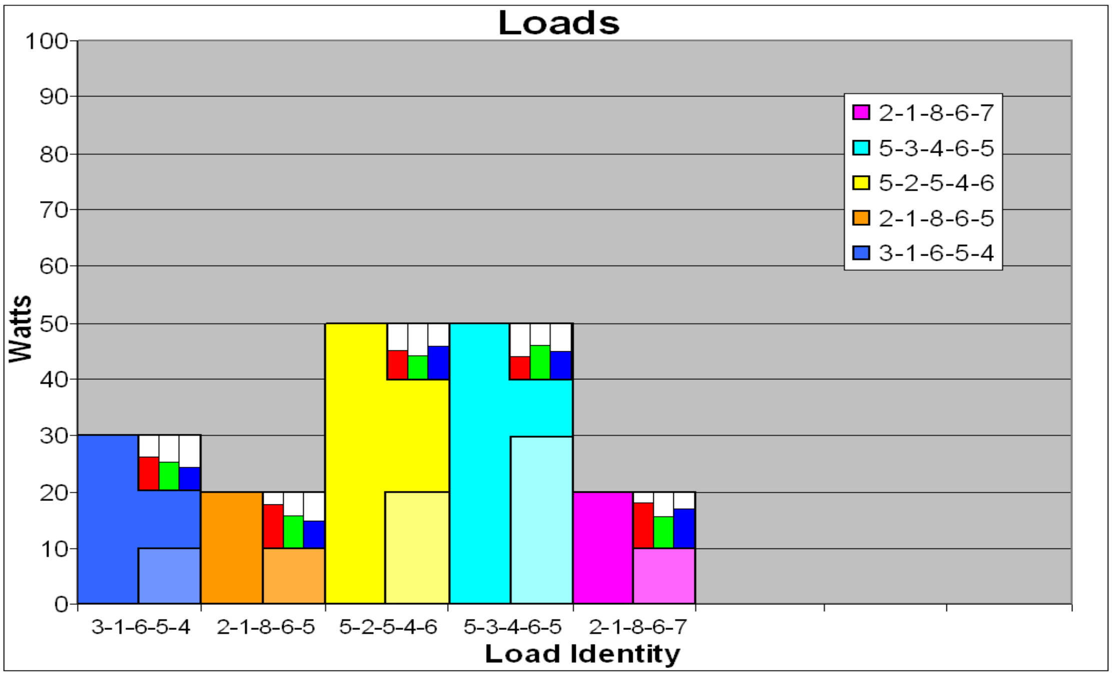


Figure 37. Loads of 30, 20, 50, 50 and 20 Watts.

Adding another identifying feature by including the 3rd, 5th, and 7th harmonic levels, as shown in **Figure 37** enables, finally, differentiation between the two 20 Watt loads, as shown in **Figure 38,** as they have different harmonic profiles.

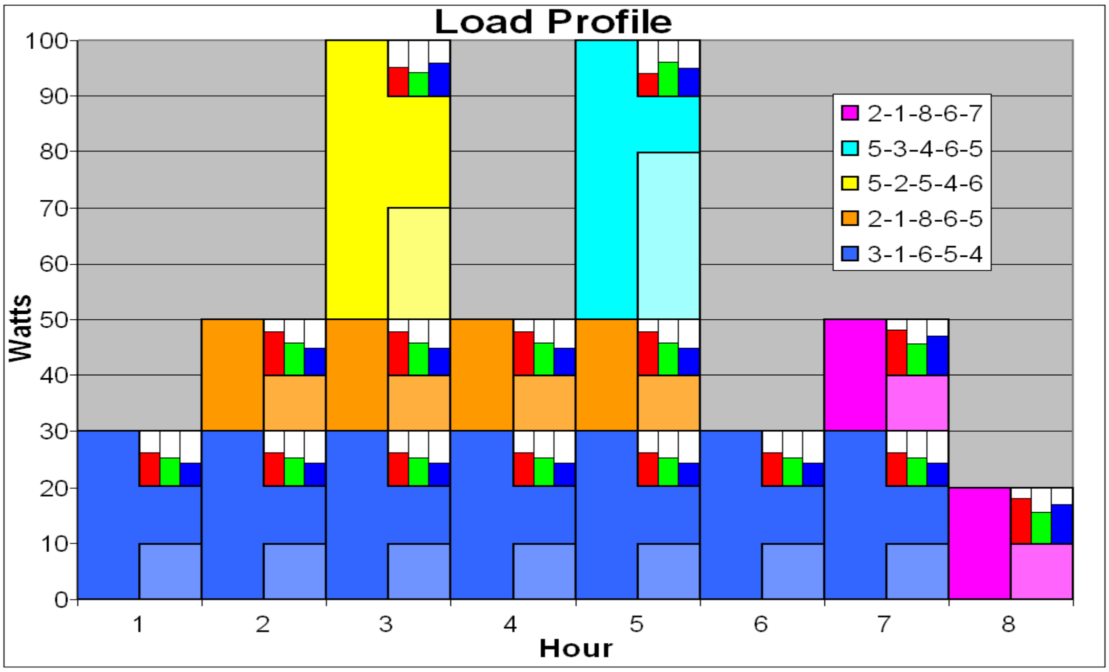


Figure 38. Daily Load Profile.

Limited information exists on this method, but to get a substantial harmonic signature, measurements would need to be made at a sampling rate approaching 10 kHz. It is reasonably simple to then recognize an individual load by analysing this signal with software designed to differentiation between a range of load signatures.

A simple low level application of this harmonic method including just the third harmonic was found and is shown in **Figure 39 & 40.**

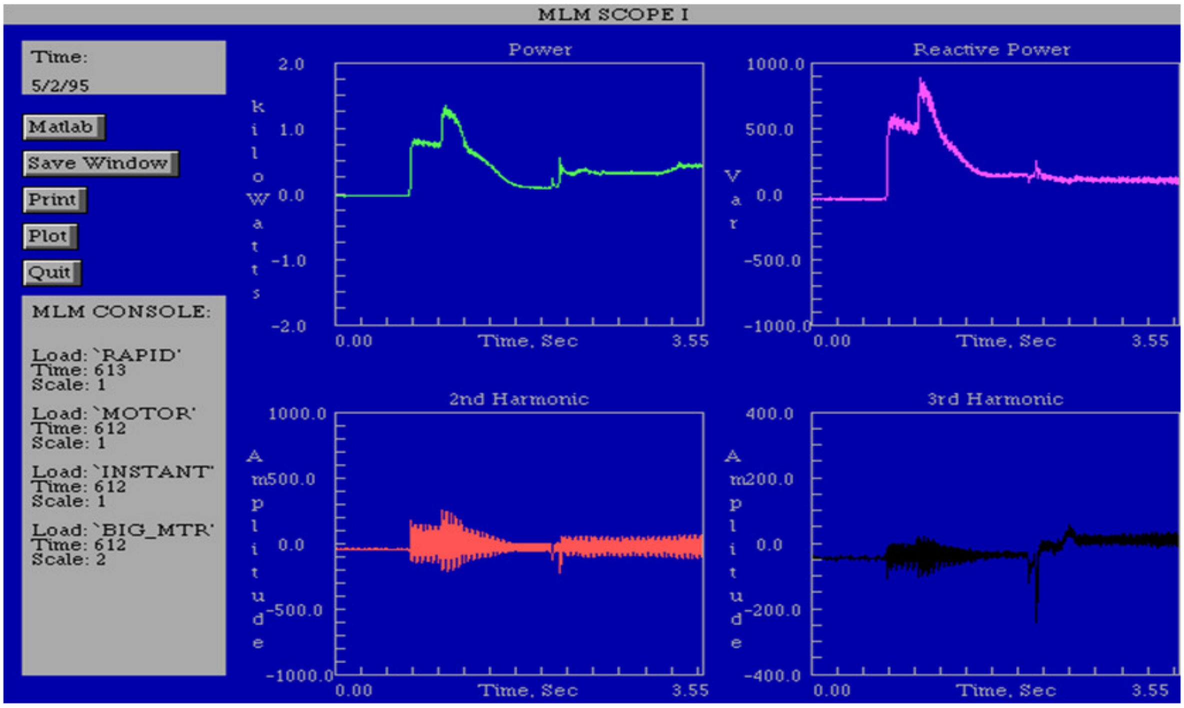


Figure 39. A simple low level application of the harmonic method [4].

Figure 39 shows the output of a prototype event detector. The four loads, a rapid start bank of lights, an induction motor, an instant start bank of lights and a large induction motor are all activated at nearly the same time. The prototype event detector is able to identify the turn-on transients of all four loads just by examining the traces of real power, reactive power, and low order harmonic content at the point of common coupling [4].

Figure 40 shows that a computer has significant 3rd Harmonic levels while an incandescent light bulb has none, allowing easy differentiation between an incandescent light bulb and a computer of even identical wattage if the 3rd harmonic is measured [5].

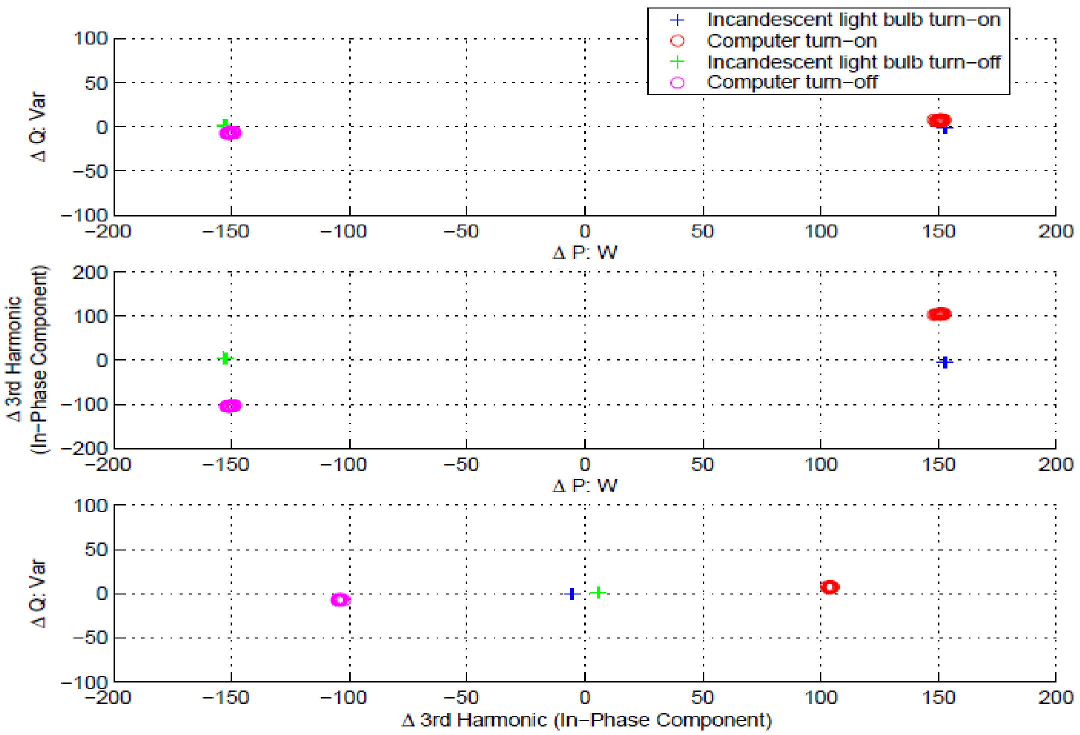


Figure 40. A simple low level application of the harmonic method [5].

A more advanced method would be to stream the instantaneous signal directly into the software, but this may not be realistic, as the software may not be able to handle the continuous raw data, so a compromise will probably have to be reached where a front end unit measures Voltage, Current, Wattage, and Harmonic levels up to about the 23rd harmonic.

It is reasonable to assume that the instantaneous voltage resolves to a perfect sine wave so this may not have to be measured. So all that needs to be measured is the instantaneous current at a single point then everything needed is in that signal, and once this information is available, it is fairly easy to recognize each individual load.

For example, a low power factor load's current waveform is shown in **Figure 41.** This waveform resolves to the model shown in **Figure 42.**

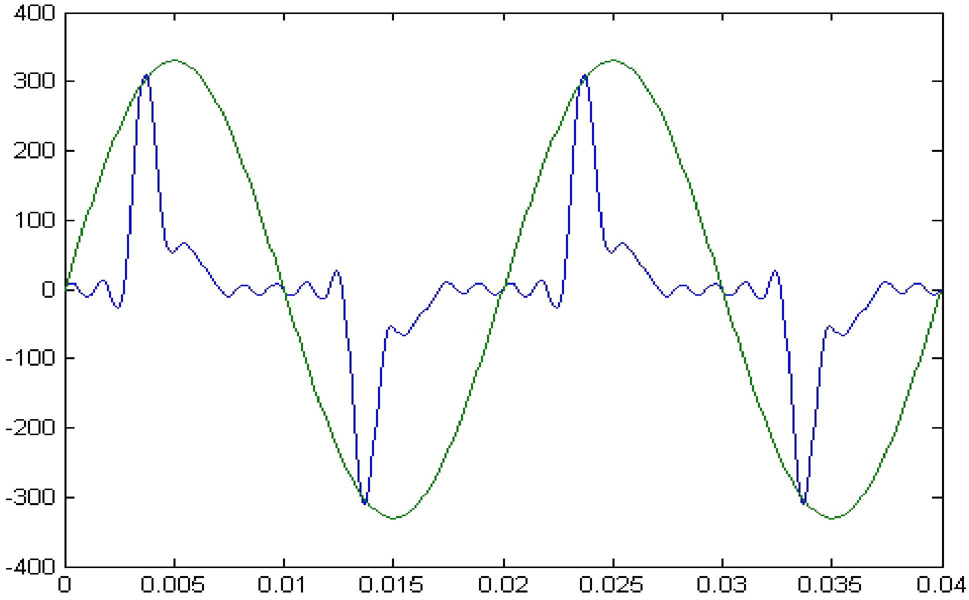


Figure 41. Voltage & Current - Low PF load .

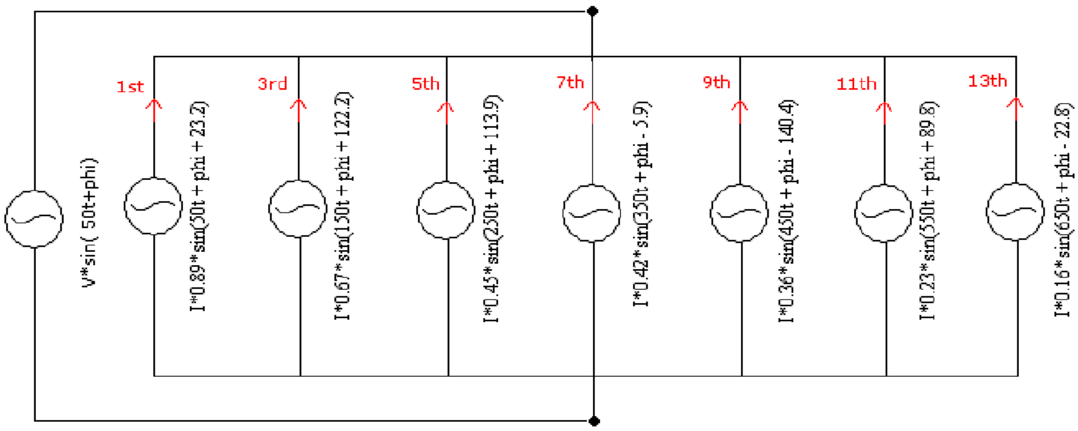


Figure 42 Model of Low PF load.

A High Power Factor load's current waveform is shown in **Figure 43**. This waveform resolves to the model shown in **Figure 44.**

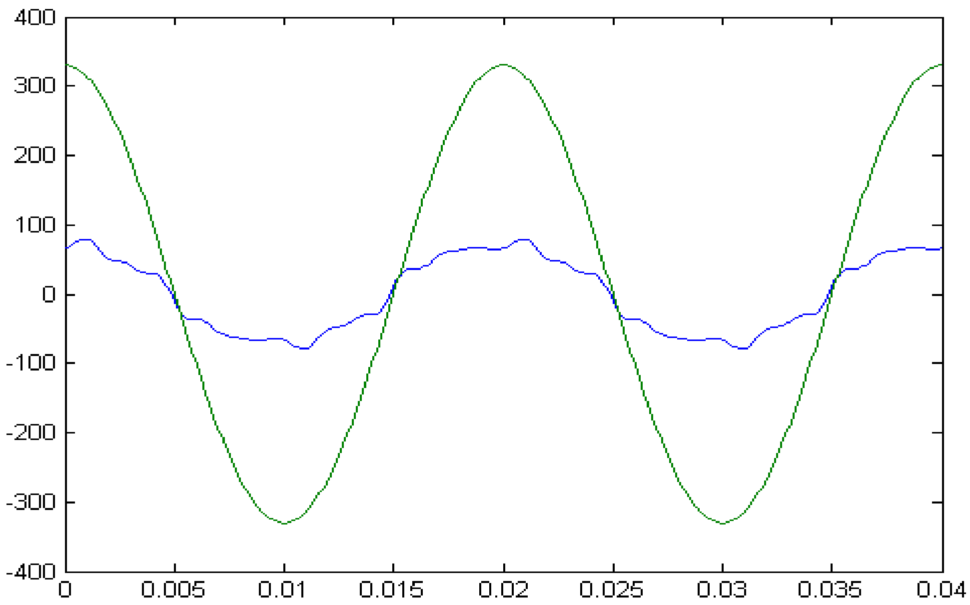


Figure 43. Voltage & Current - High PF load.

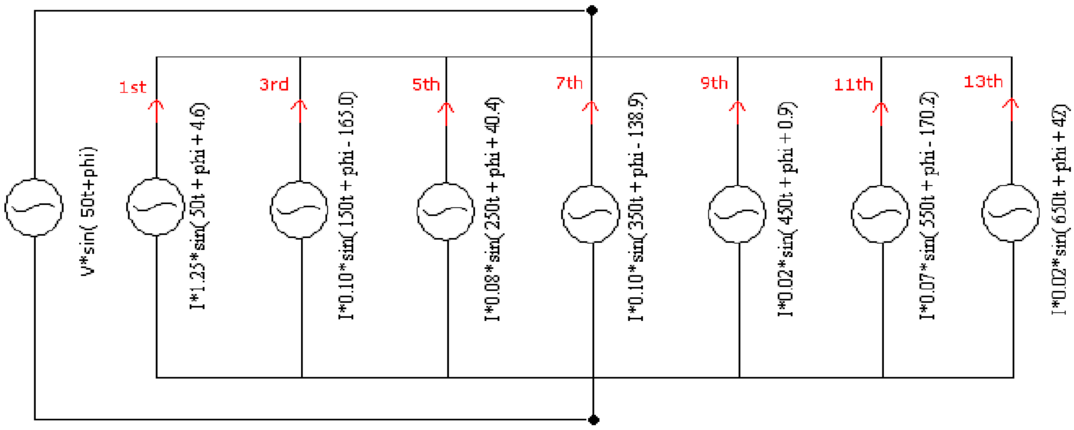


Figure 44. Model of High PF load.

Harmonics from these two loads give very different results. **Figure 45** shows the harmonics from the Low Power Factor load and **Figure 46** shows the harmonics from the High Power Factor load.

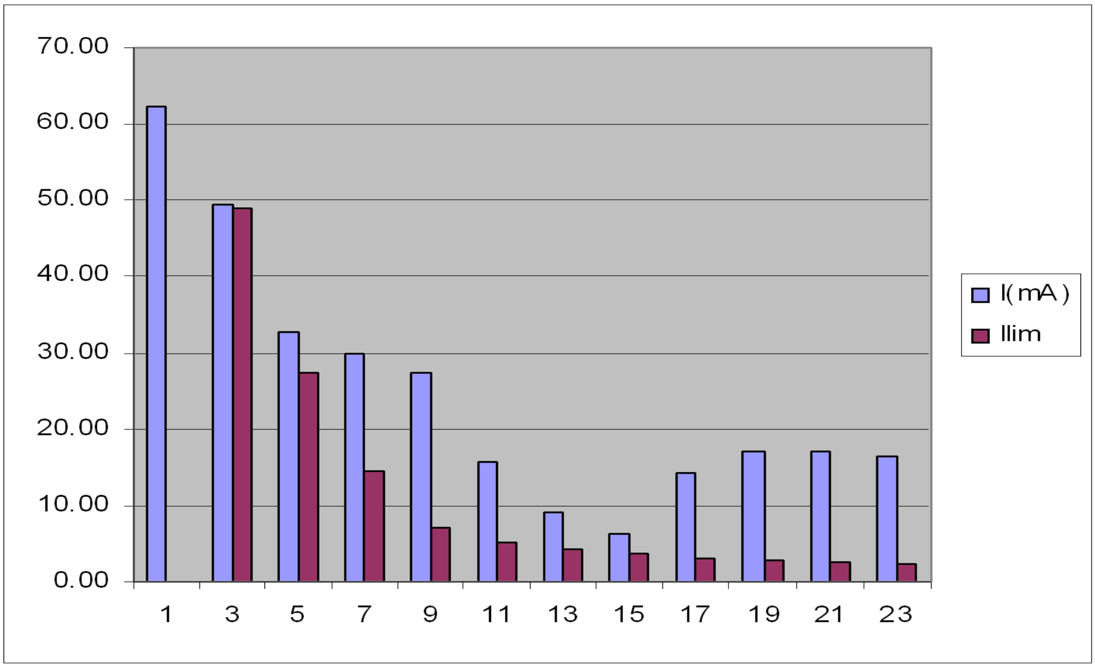


Figure 45. Low Power Factor load (Ilim is the harmonic level limit from AS/NZS 610003.2.).

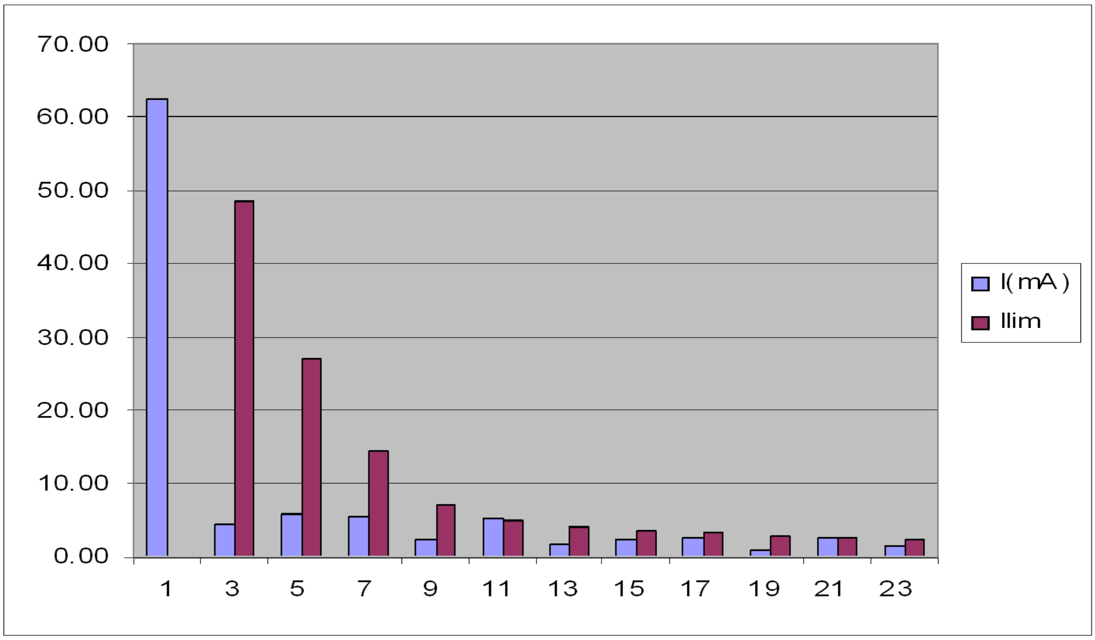


Figure 46. High Power Factor load. (Ilim is the harmonic level limit from AS/NZS 610003.2.) .

Every load can be put into such a model and so, from just the instantaneous current, you can recognize each particular load. **Figure 47** shows the harmonics from some typical non-linear loads.

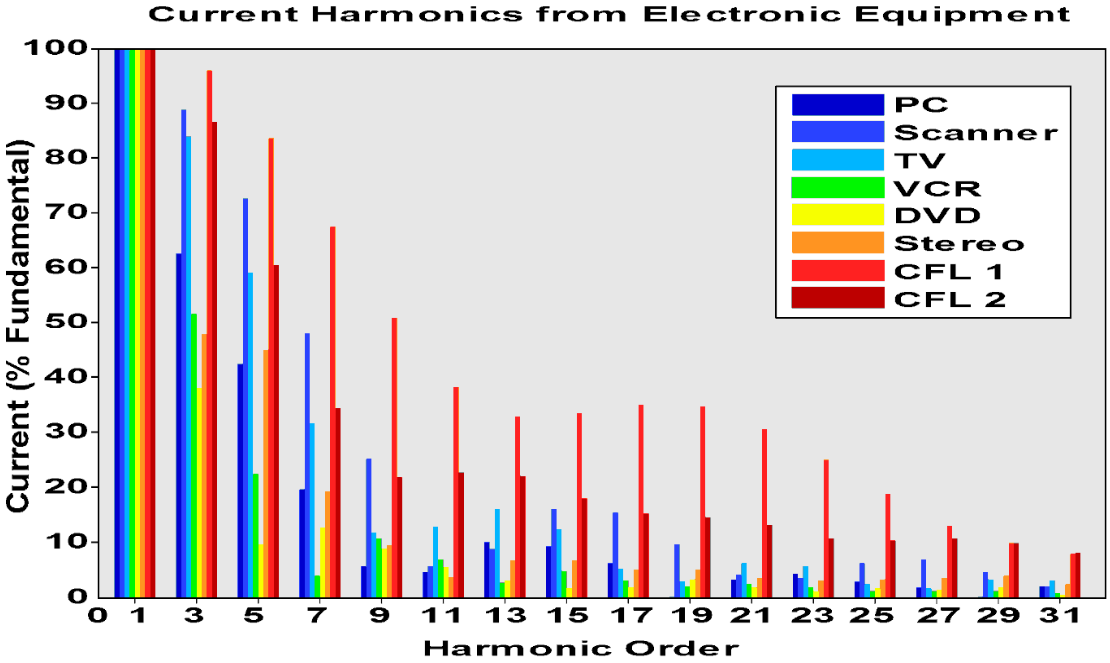


Figure 47. Typical harmonics from some common domestic loads [3].

Loads interact in magnitude, phase and frequency, but nevertheless, like as in a 60 voice choir, where each of the 60 individual voices can be recognized by their own mother; Software can be used to recognize each individual load in the cacophony of harmonics that are out there - a real Mother of a Job!

It is possible for the software to start off fairly dumb, but then to learn each profile. But it also needs to learn or already know how different loads interact with one another.

No access to the individual loads is necessary for installing sensors or making measurements. This provides a very convenient and effective method of gathering load data compared to traditional means of placing sensors on each of the individual components of the load.

So, by a sophisticated analysis of the current of the total load, the software identifies the individual loads, and their daily time of use profile.

The resulting end-use load data is extremely valuable to consumers, energy auditors, utilities, public policy makers, and appliance manufacturers, for a broad range of purposes, as a monitor placed at one point can determine how much energy goes into each of the major appliances within a home.

8.3. CFLs as Representative Modern Load

Compact fluorescent lamps are a good representative example of modern non-linear loads and are used in this research as they exhibit the typical characteristics of all modern loads, but are low cost and low power, making them easier to study within the limited budget of this research.

There has been some reluctance by users in the past to use self ballasted compact fluorescent lamps (CFLs) as poor quality products, with correspondingly low life-spans, were initially released into the marketplace. However, recent tests performed in both Australia and New Zealand indicate that the technology is now available to produce longer lasting CFLs and their market penetration is rapidly increasing. Power quality issues are expected to rise with increased market penetration, in particular increased harmonic voltage levels, and reduced power factor as almost all CFLs sold have low power factor. Power Factor compensation equipment and harmonic filtering is one mitigation option but it is not straightforward and the best approach to the problem is prevention **[14]**.

High and low power factor CFLs deliver about the same electricity savings to the user, so there is no incentive on the end user to pay more for a higher power factor CFL. Both high and low power factor CFLs also provide a useful reduction in peak demand, but network capacity savings are significantly higher for high power factor CFLs. Both low and high power factor types also provide a useful reduction in generation requirements and the potential to avoid new generation investment and provide a useful reduction in CO_2 emissions. The initial extra cost of installing high power factor CFLs rather than low power CFLs is approximately ten times less than the cost of equivalent compensation equipment, which might become necessary to counteract the degradation in power quality caused when using low power factor CFLs **[14]**.

Out of all the non-linear loads in households, Compact Fluorescent Lamps (CFLs) have been the most contentious. CFLs introduced into the market in the 1980s were supposed to replace the less efficient incandescent lamps. CFLs with separate electromagnetic ballasts were initially widely used in commercial and industrial installations, but their penetration in residential areas was limited because of the poor quality of the light provided, their large size and high price. Once the consumer had a direct plug in replacement for incandescent lamps, through the introduction of integral electronic ballasts, CFLs became more widely used in residential applications. Over the years, products improved and an increase in production volumes reduced their price.

CFLs have several advantages over basic incandescent lamps. Firstly, they only use 20% to 25% of the power consumed by an equivalent light output traditional incandescent lamp, which gives significant savings in both reduced energy costs and in the use of scares resources to produce energy. This also gives benefits for utilities who are often looking for ways to reduce overall energy demand. The expected rated life of a CFL is between 6 and 10 times that of an incandescent. CFLs typically have a rated lifespan of between 6 000 and 10 000 hours.

Unlike incandescent lamps, which have sinusoidal current waveforms, CFLs draw a distorted current when in normal operation. So, despite their advantages over electromagnetic ballasts, of greater efficiency, smaller size and weight, reduced lamp flicker and quieter operation, electronic ballasts have led to high levels of harmonic distortion. The purpose of the ballasts is to convert the voltage supplied at its input into a voltage useful in operating the lamp correctly by regulating the lamps discharge voltage and current. **Figure 48a and 48b** show actual photographs of typical CFL integral ballasts.

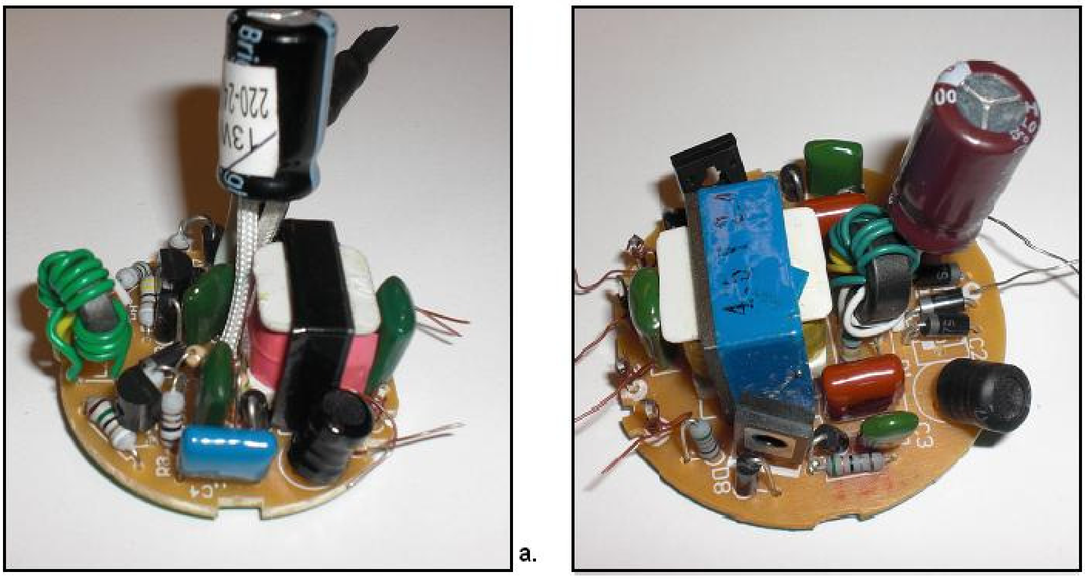

a. b.

Figure 48a & 48b. Typical CFL Ballasts.

Figure 49 shows a typical low cost CFL ballast circuit. In this circuit, the diode bridge linked with the capacitor C1 converts the single-phase 230-volt 50 Hz AC supply into

DC. The two transistors and a saturating core transformer then generate self-oscillating signals to drive the tube.

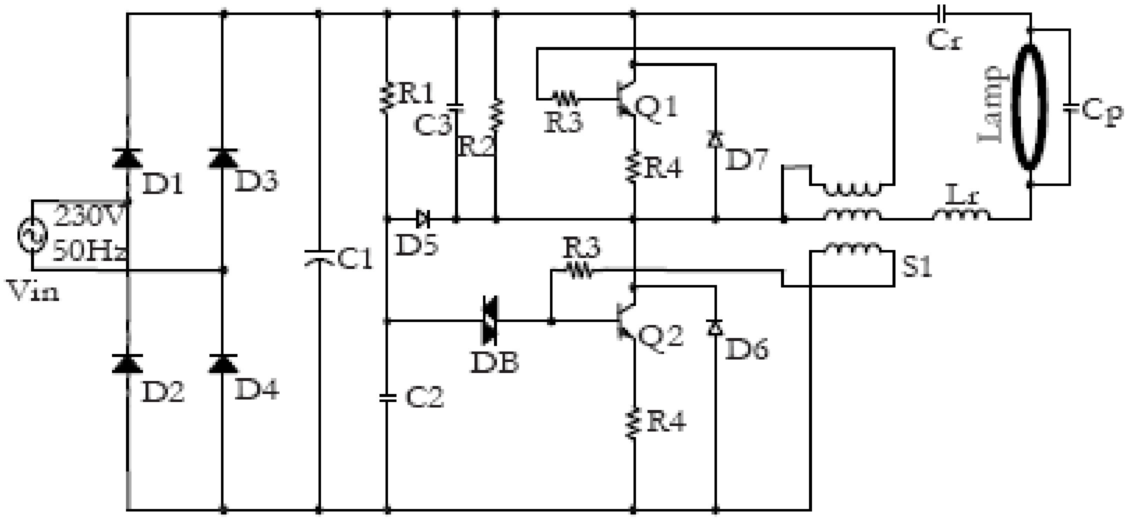


Figure 49. Schematic of typical low cost low Power Factor CFL ballast.

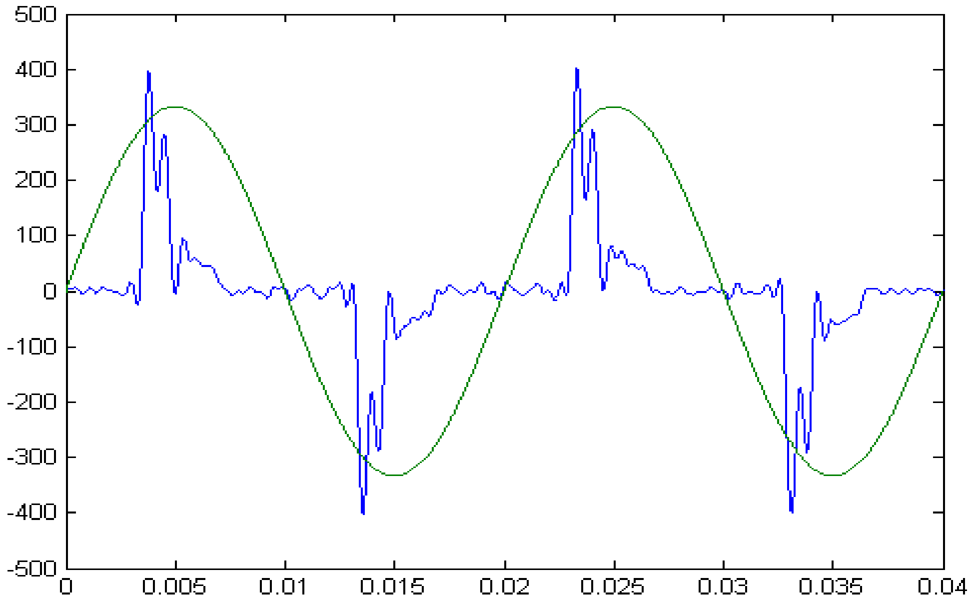


Figure 50. Current Waveform of a Low Power Factor CFL shown in Blue.

Figure 50 & 51 show the actual current waveforms and harmonic distortion levels for a typical Low Power Factor CFL.

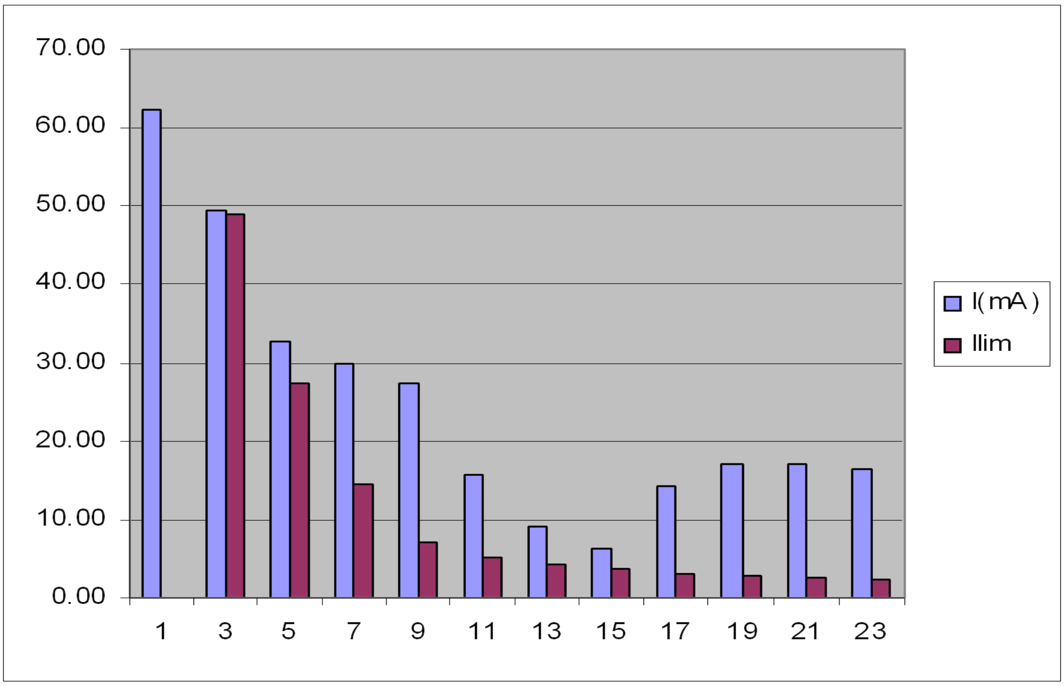


Figure 51. Harmonics produced by Low Power Factor CFL shown in Blue. (Compared with the Harmonic Standard shown in purple).

Figure 52 shows a valley-fill ballast circuit. This circuit operates in a similar manor to the low cost circuit except that capacitor 1 is replaced by a complex diode/ capacitor circuit labelled "A". The addition of these few components while seemingly trivial causes a marked reduction in the ballasts harmonic distortion, and although it adds probably less than a dollar to the cost of the item, it is considerable in a product that only sells for a few dollars, so few manufacturers sell CFLs with valley-fill ballasts.

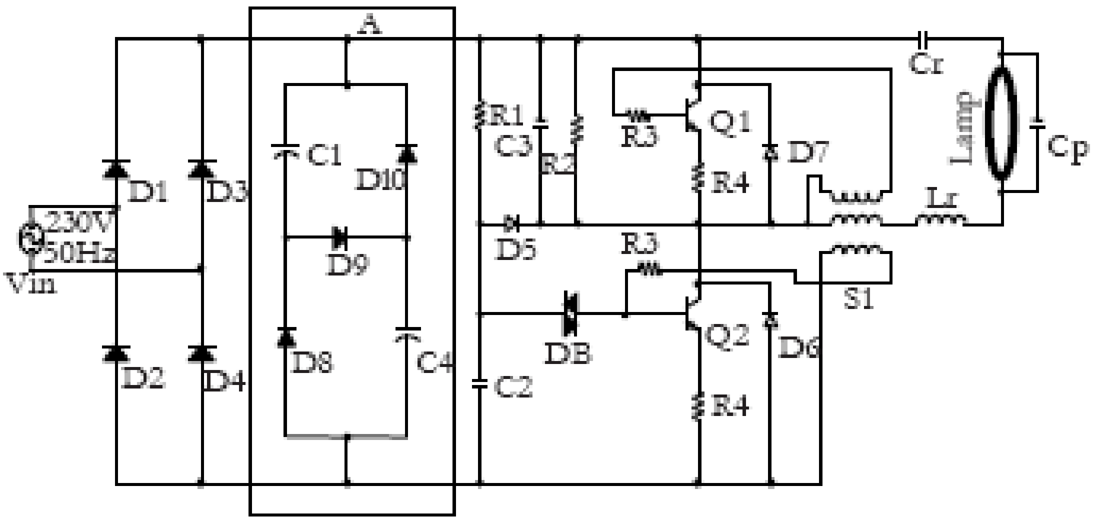


Figure 52. Schematic of typical high cost high Power Factor CFL ballast using valley fill passive Power Factor Correction circuit.

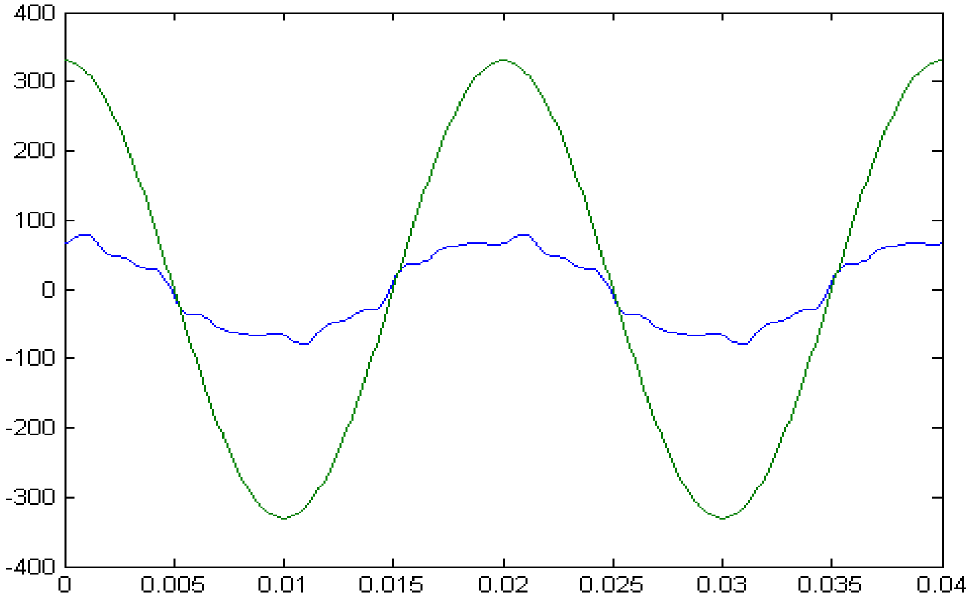


Figure 53. Current Waveform of a High Power Factor CFL shown in Blue.

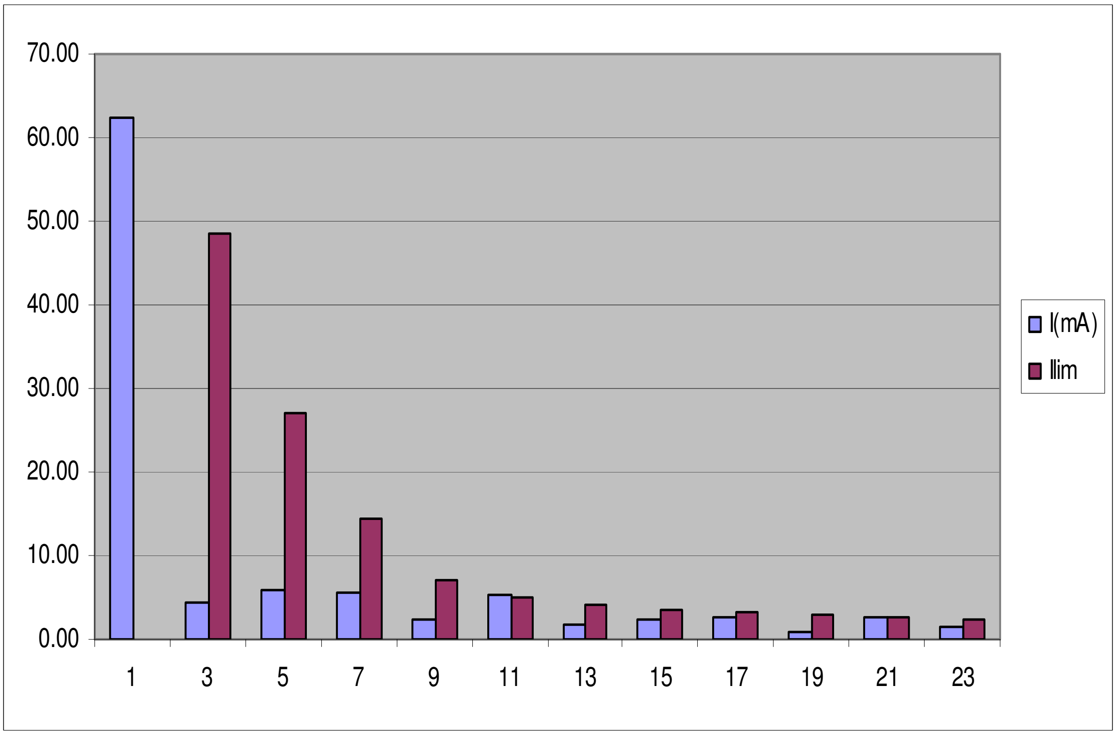


Figure 54. Harmonics produced by a High Power Factor CFL shown in Blue. (Compared with the Harmonic Standard shown in purple).

Figure 53 & 54 show actual current waveforms and harmonic distortion levels for a typical High Power Factor CFL.

The most well known local CFLs with valley-fill ballasts have a Power Factor of over 0.9 and low Total Harmonic Distortion. Unfortunately most manufacturers still only use the simplest basic ballast circuit, mainly because of its lower cost. There is also an additional slight risk of earlier failure in the valley-fill product due to the additional component count.

8.4. CFLs Harmonic Interaction

One of the characteristics of harmonics is that each harmonic order has a magnitude and a phase angle corresponding to the phase between harmonic current and voltage. And as the phase angles of each harmonic in different loads are not always the same, the overall magnitude for a harmonic will be equal to, or less than the simple sum of the harmonics as the vector sum of harmonics from two different loads of the same order is given by:

Vector Sum:

$$= I_{1n}\sin(nwt+\Phi_{1n}) + I_{2n}\sin(nwt+\Phi_{2n})$$
$$= (I_{1n}\cos\Phi_{1n} + I_{2n}\cos\Phi_{2n})\sin(nwt) + (I_{1n}\sin\Phi_{1n} + I_{2n}\sin\Phi_{2n})\cos(nwt)$$

Magnitude:

$$= A\sin(nwt) + B\cos(nwt)$$

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

Where:

I_{1n} = current in harmonic order n of load 1

I_{2n} = current in harmonic order n of load 2

Φ_{1n} = phase angle of harmonic order n of load 1

Φ_{2n} = phase angle of harmonic order n of load 2

As several investigations report that an average household uses around 2 to 5 CFLs at any one time, the harmonic interaction between 2 to 5 CFLs was investigated. And as both high and low power factor lamps are used in homes, we investigated the interaction of both types of lamps, the characteristics of which are shown in **Figures 49, 50 & 51**, and **Figures 52, 53 & 54** respectively.

8.4.1. Experiments

Various combinations of two to five CFLs were plugged in at the same time and their outputs measured in order to observe how their harmonics interacted. At each harmonic order the error was calculated and the average value of the error determined. Fifteen experiments were carried out outlining different combinations of both Low Power Factor and High Power Factor lamps. **Figure 55** shows harmonic magnitude versus difference between harmonic angles.

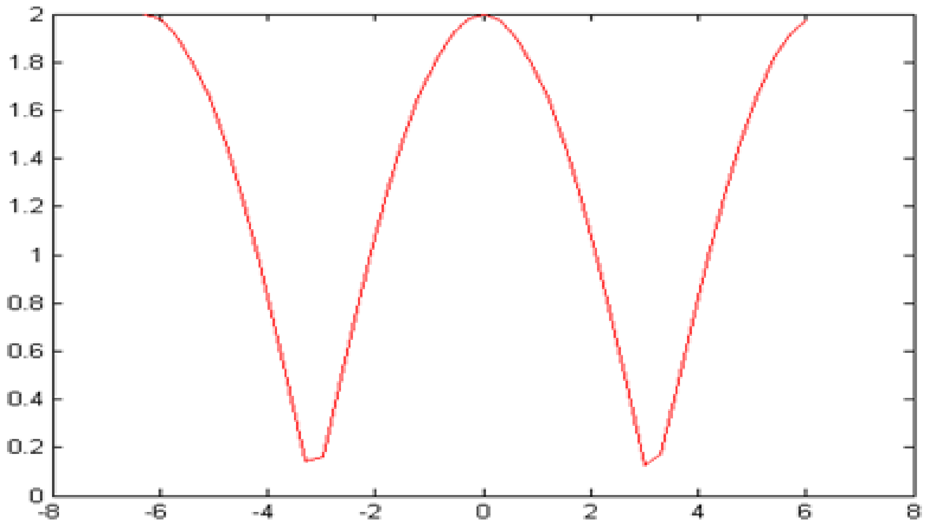


Figure 55. Harmonic Magnitude vs difference between angles in radians.

8.4.2. Results

Combining Two Low Power Factor Lamps

Table 1 Shows that when two low lower factor lamps are combined the combined THDi and Power Factor are better than those observed individually. This is caused by the partial cancellation of harmonics with different phase angles. **Figure 56** shows the spectrum analysis comparing the simple sum of the harmonic magnitudes and the measured harmonic magnitudes of the combined loads.

As expected, harmonic magnitudes of the combined load were always lower than the sum of the individual magnitudes. For all the orders considered, the average value of the error is 7.38%. If we consider only the first thirteen orders the error is only 3.65%. The low error could be explained by the fact that the ballasts are similar; therefore phase angles associated with the harmonic currents are close.

Table 1 Combining Two Low Power Factor Lamps.

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

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

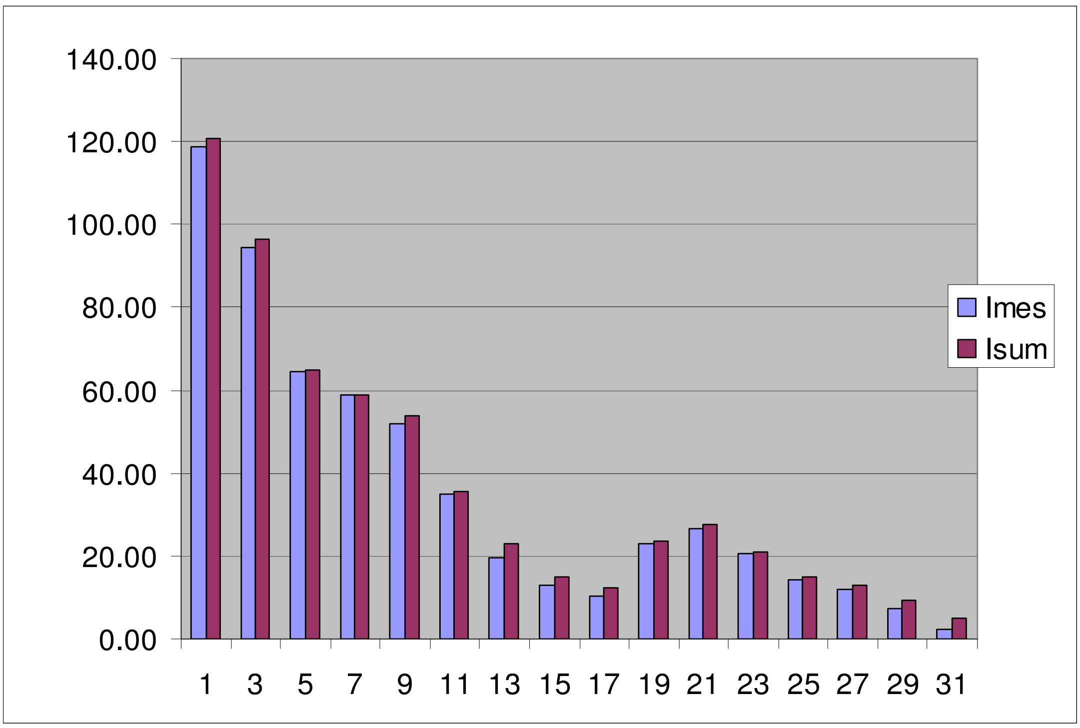


Figure 56. FFT sum and measured combined load of two LP lamps.

COMBINING ONE LPF LAMP AND ONE HPF LAMP

Table 2 shows that when one low lower factor lamp is combined with one high power factor lamp, the combined THDi and Power Factor are better for the low power factor lamp and worse for the high power factor lamp with the power factor dropping to 0.76. Note that the difference between the HPF Lamp and LPF Lamp is clearly shown by the difference between both their power factor (PF) and their total harmonic distortion (THDi) (shown highlighted in yellow in **Table 2**.)

Figure 57 shows the spectrum analysis comparing the simple sum of the harmonic magnitudes and the measured harmonic magnitudes of the combined loads.

The simple sum of harmonic magnitudes is close to the overall magnitude for each order with the average error of 18.18% which is higher than the error calculated for the two low power factor lamps because of the significant ballast differences between the LPF lamp and the HPF lamp.

Table 2 Combining High Power and Low Power Factor Lamps.

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

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

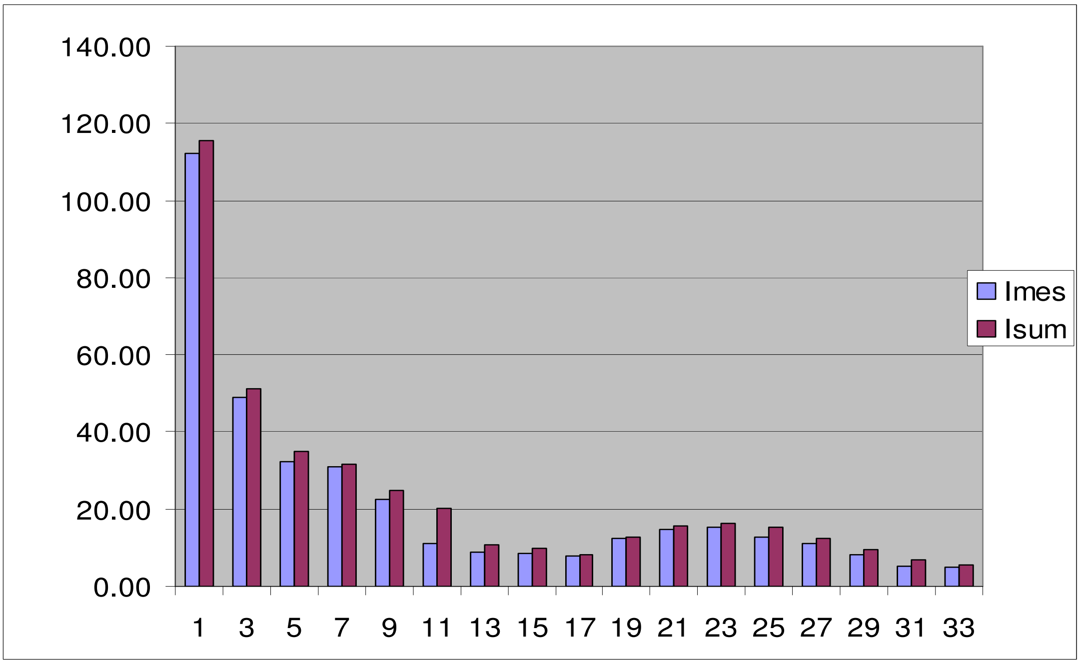


Figure 57. FFT sum and measured combined load of one LPF lamp and one HPF lamp.

COMBINING TWO HPF LAMPS

Figure 58 shows the spectrum analysis comparing the simple sum of the harmonic magnitudes and the measured harmonic magnitudes of two combined HPF lamps. The performance of the two combined HPF lamps is even better than the individual HPF lamps with a combined Power Factor of 0.97, THDi equal to 13.04% and K-Factor of only 2.55. The average error between the simple sum of the harmonic magnitudes and the measured harmonic magnitude was 6%.

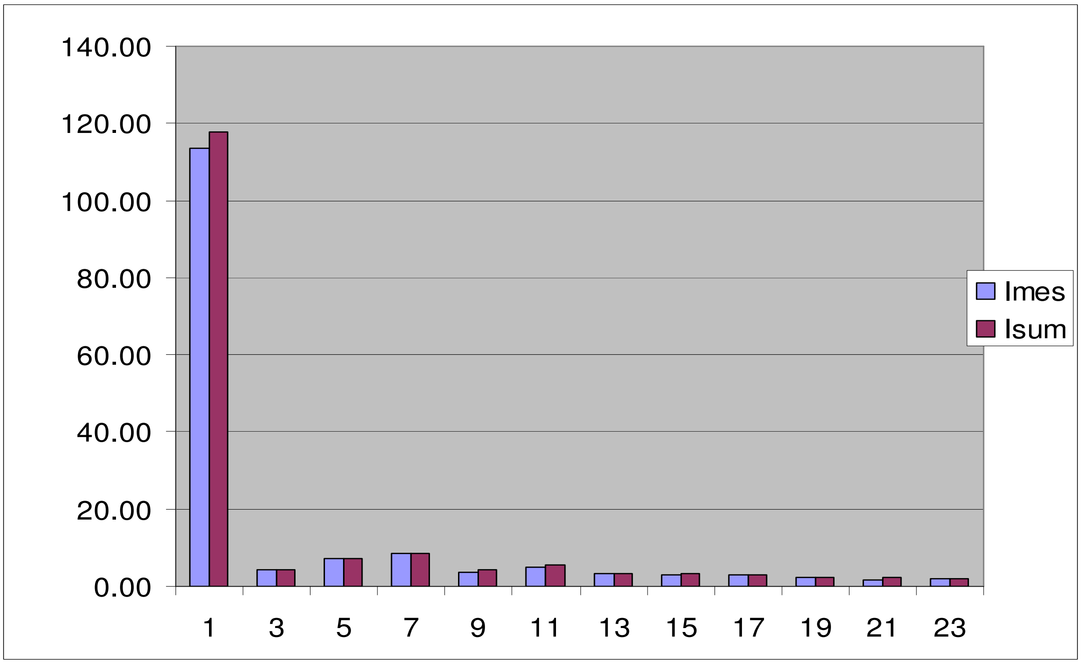


Figure 58. FFT sum and measured combined load of two HPF lamps.

MULTI COMBINATION LAMP RESULTS

Interaction between low and high power factor lamps is complex and the inclusion of high power factor lamps with low power factor lamps dramatically improves the combined power factor as shown in **Figure 59.**

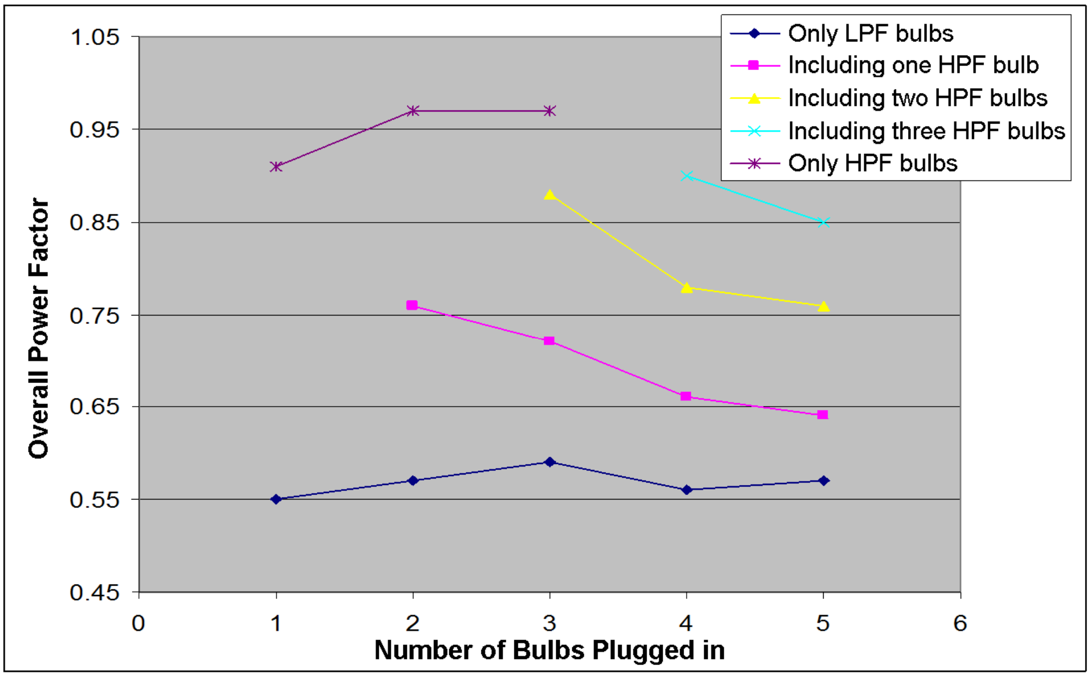


Figure 59. Changes in Power Factor with Lamp combination

When considering the impact on harmonic distortion, **Figures 60** shows the interaction between low power factor and high power factor lamps. Further analysis shown in **Figure 61** indicates that including even 1 high power factor lamp for every three low power factor lamp, dramatically reduces the overall harmonic distortion.

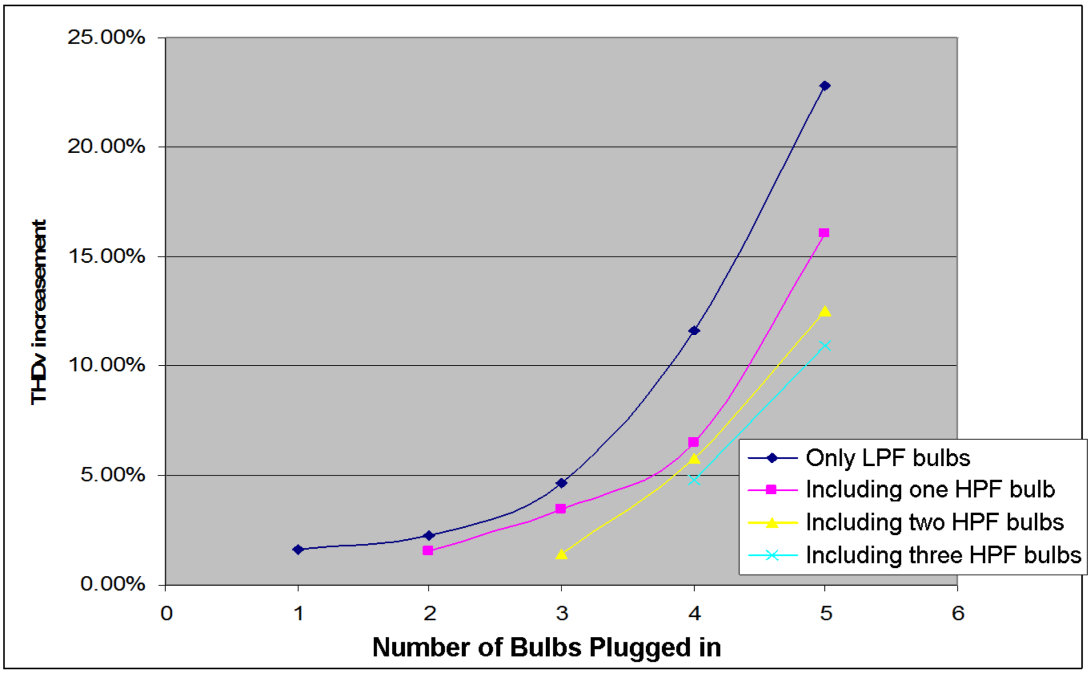


Figure 60. THDv in % for the load combinations.

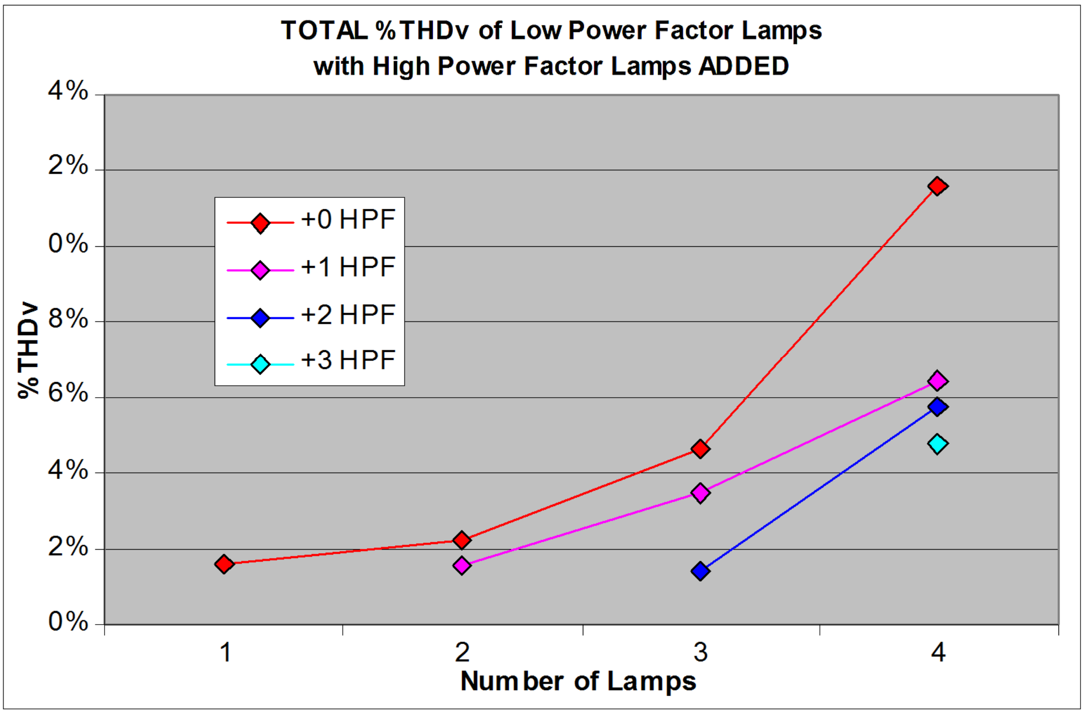


Figure 61. Accumulative Harmonics.

8.5. CFLs Harmonic Limits

Besides complying with local requirements for safety, light output, lifespan, energy efficiency, and so on, CFLs are also supposed to comply with local standards for power quality.

At the start of this research in late 2008, the then current Australian/New Zealand standard relating to power quality issues such as harmonic content was AS/NZS 61000.3.2:2007, **[15]** directly derived from the international standard, IEC 61000.3.2:2007 **[16]**. AS/NZS 61000.3.2:2007 **[15]** identifies CFLs as class C **[A6]** lighting equipment. However a clause in the standard states that class C equipment with input power of less than or equal to 25W must instead comply with the lesser requirements of class D **[A6]**. In particular, it specifies that discharge lighting equipment, such as CFLs, having an active input power of less than or equal to 25 Watts, only need to comply with the much more lenient requirements as shown in this extract from AS/NZS 61000.3.2:2007 **[15]**:

b) Active input power ≤25 W

Discharge lighting equipment having an active input power smaller than or equal to 25 W shall comply with one of the following two sets of requirements:

- the harmonic currents shall not exceed the power-related limits of Table 3, column 2, **or:**
- the third harmonic current, expressed as a percentage of the fundamental current, shall not exceed 86 % and the fifth shall not exceed 61 %; moreover, the waveform of the input current shall be such that it begins to flow before or at 60°, has its last peak (if there are several peaks per half period) before or at 65° and does not stop flowing before 90°, where the zero crossing of the fundamental supply voltage is assumed to be at 0°.

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

NOTE - Widespread use of devices meeting this criterion can cause interference in networks, particularly networks using ripple control signalling. It is intended to delete this second criterion from October 2010 subject to the outcome of a review to be carried out on the effect of the mass introduction of these lamps.

Table 3 – Limits mainly for Class D equipment

NOTE - Refer to Clause 7.3b) for limits for Class C equipment

Harmonic order n	Maximum permissible harmonic current per watt mA/W	Maximum permissible harmonic current A
3	3,4	2,30
5	1,9	1,14
7	1,0	0,77
9	0,5	0,40
11	0,35	0,33
$13 \leq n \leq 39$ (odd harmonics only)	$\frac{3,85}{n}$	See Table 1

The second bullet point in b) is much more lenient for CFLs than the first bullet point in b).

In 2009, partially through lobbying by the author, AS/NZ 61000.3.2:2007 **[15]** was amended as AS/NZS 61000.3.2:2007 Amt A (31st October 2009) **[17]** Electromagnetic compatibility (EMC) Limits for harmonic current emissions, and Clause 7.3 Limits for Class C equipment part b) became more stringent and was changed, (noting in particular the section highlighted in yellow,) to read:

b) Active input power ≤25 W

Discharge lighting equipment having an active input power smaller than or equal to 25 W shall comply with one of the following two sets of requirements:

- the harmonic currents shall not exceed the power-related limits of Table 3, column 2, or:
- the third harmonic current, expressed as a percentage of the fundamental current, shall not exceed 86 % and the fifth shall not exceed 61 %; moreover, the waveform of the input current shall be such that it begins to flow before or at 60°, has its last peak (if there are several peaks per half period) before or at 65° and does not stop flowing before 90°, where the zero crossing of the fundamental supply voltage is assumed to be at 0°.

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

  NOTE - Widespread use of devices meeting this criterion can cause interference in networks, particularly networks using ripple control signalling. It is intended to delete this second criterion from October 2010 subject to the outcome of a review to be carried out on the effect of the mass introduction of these lamps.

Notwithstanding the above, in New Zealand, for integrated compact fluorescent lamps (CFLIs) having an active power input in the range 14 W to 25 W (inclusive) the harmonic currents shall not exceed the power-related limits of Table 3, column 2.

NOTE - this requirement does not cover special purpose CFLIs such as Lusters, Candles and Fancies or reflector lamps.

Table 3 – Limits mainly for Class D equipment

NOTE - Refer to Clause 7.3b) for limits for Class C equipment

Harmonic order n	Maximum permissible harmonic current per watt mA/W	Maximum permissible harmonic current A
3	3,4	2,30
5	1,9	1,14
7	1,0	0,77
9	0,5	0,40
11	0,35	0,33
$13 \leq n \leq 39$ (odd harmonics only)	$\frac{3,85}{n}$	See Table 1

Unfortunately, this New Zealand only requirement is not being met or policed, nor is it called up in the recently published CFL Minimum Energy Performance Standard [18] or even in the New Zealand Energy Star Requirements for CFLs [19] or in the new Electricity (Safety) Regulations 2010 [9].

9. MITIGATION OPTIONS

This research has ascertained that the New Zealand Power Distribution Network is "weak" having higher impedance than most first world countries, and that power quality is low within the New Zealand Power Distribution Network [11].

The two main issues which need to be addressed with regard to harmonics in New Zealand are; high background levels of harmonics; and high harmonic levels from non-linear loads in general and CFLs in particular.

The high background level of harmonic distortion is being addressed in part by the current upgrade to the HVDC link and by increased generation mid North Island. The long awaited upgrade to the High Voltage DC Link will not only strengthen the 'weak' New Zealand power distribution network, but also reduce the 'background' harmonic distortion currently injected into the network by the old 1960s mercury arc valve technology of Pole 1.

The high harmonic levels from non-linear loads in general and CFLs in particular is not easily addressed as mitigation of the harmonic distortion caused by multiple small non-linear loads is very difficult once they are in the network due to the dispersed nature of these loads within the network.

9.1. UPGRADE TO HVDC LINK

The HVDC grid upgrade has THREE Stages1 [11]:

Stage 1, which is due by 2012, is the installation of a new thyristor-based 700 MW pole at Haywards and Benmore to replace the existing Pole 1. This will bring the HVDC inter-island link, up to a 1000 MW capacity.

Stage 2, which is due by 2014, is the installation of a new dynamic reactive power compensation facility at Haywards to enable bi-pole operation of at least 1200MW.

Stage 3, which is due beyond 2017, is planned to increase the overall capacity of the HVDC link to 1400 MW.

Figure 62 shows the HVDC with existing assets in **blue**, Stage 1 in **red**, Stage two in **green** and Stage 3 in **purple**.

The HVDC link is a crucial component within the New Zealand power system. It allows the transfer of power from the South to the North Island during peak demand periods and from the North to the South Island during dry periods. But the ability of the link to transfer power is constrained by certain aspects of both DC and AC power systems **[11]**.

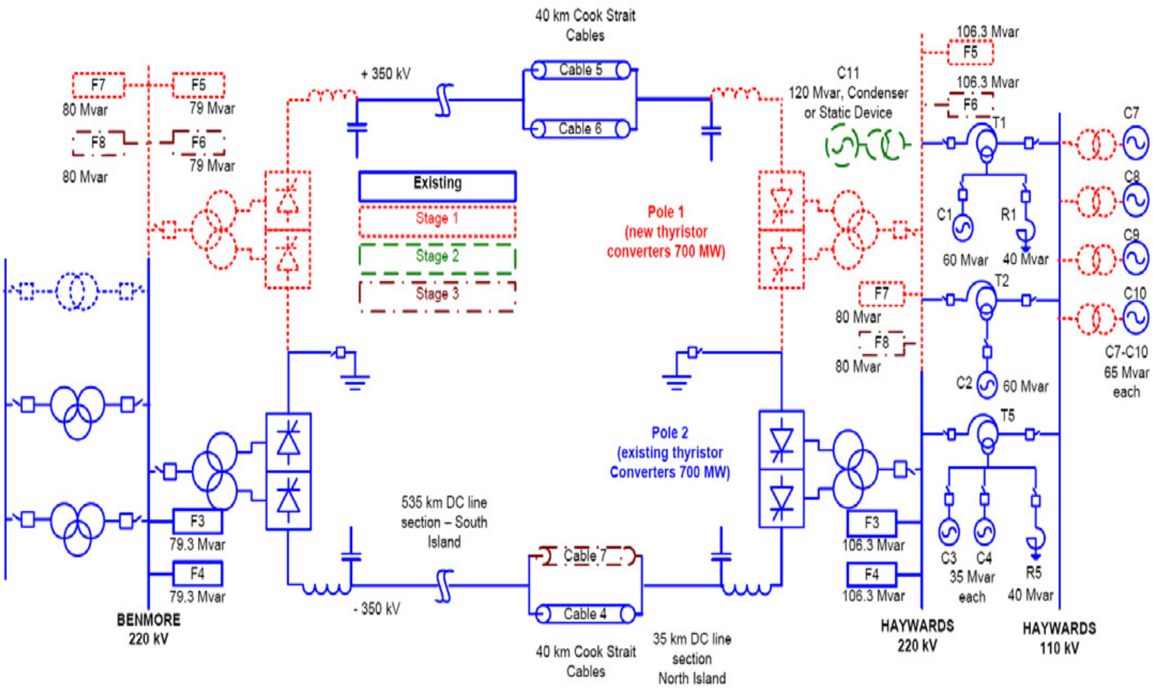


Figure 62. HVDC link single line diagram showing existing equipment and the three planned stages [11].

There are variable constraints such as generation availability and demand in each Island and fixed constraints such as the physical HVDC converter equipment and the connected AC and DC systems, such as the capacity of the DC cables under Cook Strait or the capacity of a linked AC system transmission line **[11]**.

For the New Zealand HVDC link the Haywards/Wellington region remains a weak system with a low Short Circuit Ratio (SCR) and with minimal local generation. This weak system was identified in the initial planning and design stage of the original HVDC link and required strengthening with the use of rotating synchronous condensers capable of fast voltage regulation and able to provide mechanical inertia to the AC system **[11]**.

So with respect to the New Zealand power distribution network, this upgrade will decrease the background harmonics levels in the network and will strengthen it as well, making it less susceptible to harmonics.

Although Pole 1 was temporary “stood down” in 2007, it has still been used since then. Pole 1 was partially decommissioned late in 2009, but half of Pole 1 was refurbished and is still in use. Pole 1’s planned decommissioning date is near the end of 2012. Pole 3 is similar to pole 2, and Transpower have indicated that the HVDC link upgrade will now include additional filtering to upgrade pole 2 as well **[11]**.

9.2. NETWORK POWER QUALITY CORRECTION

Generally, up till now, the distortion in the network caused by small non-linear loads has been ignored. Yet the combined effect of the wholesale introduction of small, non-linear loads can be even more detrimental than one large distorting load acting as a harmonic source because the power quality requirements for small loads are much less stringent than for large ones. For example **Figure 63** shows that although each CFL on its own may pass the harmonic current requirement, CFLs are not usually found individually, and it can easily be seen that just 10 CFL at the same location would far exceed the harmonic current requirement for an equivalent single load. The black line in **figure 63** shows the Harmonic Limit according to AS/NZS 61000.3.2 **[17]**.

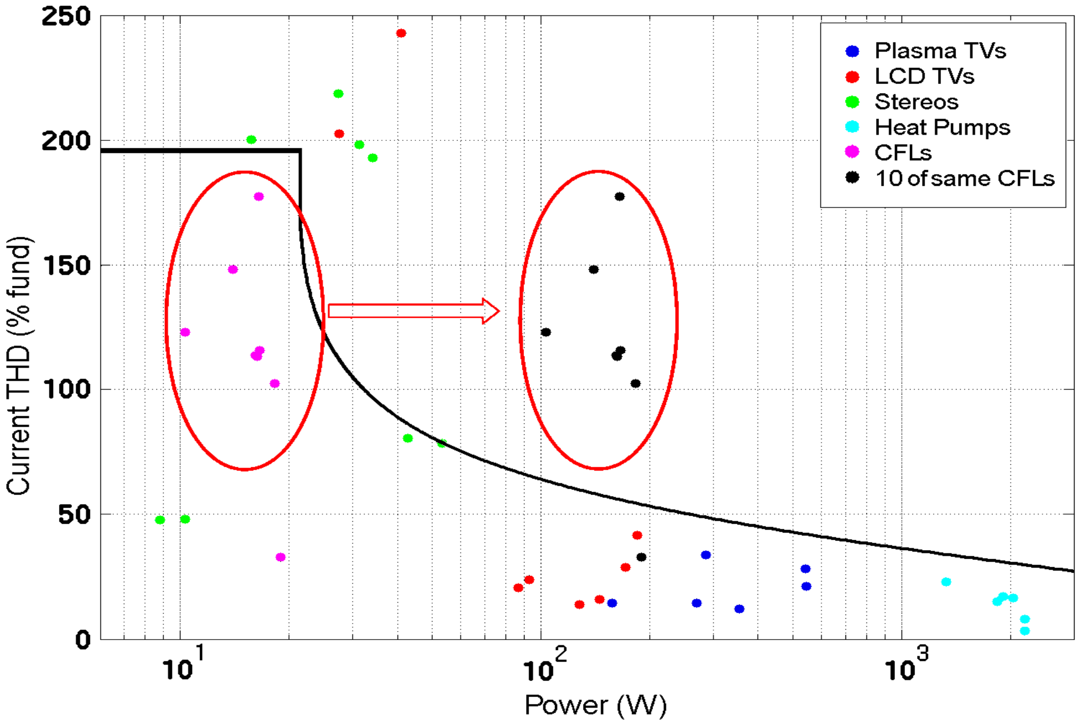


Figure 63. Comparison of current distortion between categories of appliance. Multiple CFLs are typically found in a home and therefore have increased power [20].

A further complication is that mitigation of the harmonic distortion caused by multiple small non-linear loads is also very difficult once they are in the network due to the dispersed nature of these loads within the network [3] [24].

While power factor correction and harmonic filters can be retrofitted at or near large disturbing loads, it is not as easy to retrofit power factor correction and harmonic filters onto each small disturbing load, so harmonic filters are usually designed and installed at points of common connection higher up in the network. However the most cost effective way of avoiding these retrofit remedies is to ensure that each individual non-linear load is, at product development stage, designed to cause the lowest level of harmonic injection that is practically possible at a reasonable price, as correcting the problem retrospectively higher up in the network costs up to 10 times more than the extra cost of using loads that produce less distortion in the first place [24].

The widespread use of, and the constant rise in, electric energy use has caused the growth of the residential power distribution network and has increased the obligations of the electricity companies for better power quality. Power quality consists of stable frequency and voltage, and low harmonic distortion. Unfortunately the proliferation of small non-linear loads is making power companies task difficult and represents a possible source of faults and troubles within the power distribution system [6].

Some power distributors are concerned with disturbances that may occur within the premises of their customers since such customers may attempt to fix the blame for local interaction problems on the power quality as supplied by the utility [23].

A further complicating factor when trying to find such dispersed disturbances in the power distribution network is that domestic meters do not usually directly measure harmonic distortion. This limitation is rapidly being removed however as the current push to introduce “smart meters” also implies that the utilities will soon be able to directly measure harmonic distortion at the users premises, and bill or fine the user accordingly, rather than just allocating this cost to all consumers on a pro rata basis as they do at the present. So, as most if not all domestic users contracts state that they must maintain a power factor of greater than 0.95 or else pay a penalty, those users who have ‘done the right thing’ in moving to more energy efficient, but more power degrading, non-linear loads may soon be asked to pay a fine for doing so, and/or pay a higher rate for their electricity.

In typical modern electronic circuits the current waveform distortion that contributes to a reduced power factor also causes voltage waveform distortion and overheating in the neutral cables. For this reason, international standards such as IEC 61000.3.2 have been established to control current waveform distortion by introducing limits for the amplitude of current harmonics. To comply with these standards, designers use circuits that force the current waveform to be near sinusoidal and in-phase with the voltage. These circuits are known as Power-Factor Correction circuits and Harmonic Filter circuits.

Improving the power factor also decreases the harmonic distortion as the relationship between True Power Factor $\mathbf{PF_T}$ Displacement Power Factor $\mathbf{PF_D}$ and Total Current Harmonic Distortion $\mathbf{THD_I}$:

$$\mathbf{PF_T} = \frac{\mathbf{PF_D}}{\sqrt{\mathbf{1+(THD_I)^2}}}$$

Figure 64 shows this in graphical form: The coloured lines indicate $\mathbf{PF_D}$. To find $\mathbf{PF_T}$ move along the $\mathbf{PF_D}$ line until you get to the $\mathbf{THD_I}$ then read off the $\mathbf{PF_T}$ on the **Y** axis. For example if $\mathbf{PF_D}$ = 0.4 and $\mathbf{THD_I}$ = 100% then $\mathbf{PF_T}$ = 0.3.

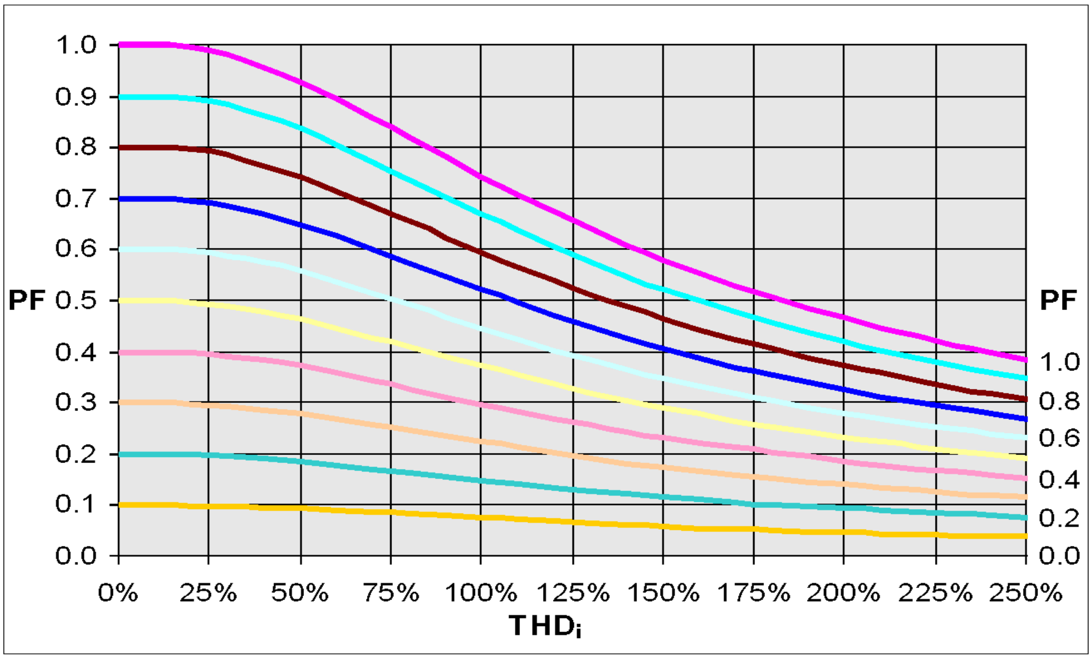


Figure 64. Relationship between True Power Factor $\mathbf{PF_T}$ Displacement Power Factor $\mathbf{PF_D}$ and Total Current Harmonic Distortion $\mathbf{THD_I}$.

9.3. RESIDENTIAL POWER QUALITY CORRECTION

Power quality is an increasing concern for power utilities and their customers. Although power factor correcting equipment and harmonic filters can readily be designed and installed at or near the terminals of large loads, it is not as easy or cost effective to retrofit these on each small disturbing load. So the best way of avoiding costly remedies is to ensure that each and every individual non-linear load causes the lowest level of harmonic injection that is practically possible at a reasonable price [24].

A power quality correction unit is proposed to reduce the distortions caused by non-linear loads as close to source as possible. (See **Figure 65**.)

The power quality correction unit can be incorporated into any load or at the first point of common coupling. This will reduce the need to install expensive, large, power quality correction devices higher up in the electrical power network.

The power quality correction unit has the ability to correct power distortions of any kind, be it power factor, phase, frequency, harmonic distortion, etc.

The power quality correction unit shown in **Figure 66** operates in the following manner:

1. Sample the electrical power network to ascertain its characteristics.
2. Compare the sample of the electrical power with a stored sample of an ‘ideal’ electrical power network.
3. Adapt its input and/or output, current or voltage, frequency or phase, in whatever way or combination which will improve the power quality characteristics of the load. The unit does this by either drawing power from the power network or putting power into the power network, using electronic switching devices.
4. Monitor the electrical power network to ensure the correction is happening and that the system is stable.
5. Return to step 1.

In essence the method of control is adaptive and not predetermined. The power quality correction unit adapts its output to achieve its prime objective of maintaining, correcting, or improving power quality of the network it is connected to.

In some circumstances, if more than one unit is connected to the electrical power network, the power quality correction unit may need to synchronise with the other power quality correction units.

The power quality correction unit has a further wide range of potential applications within the electrical and electronic industry such as the better ‘matching’ of remote distributed generators and loads to the power distribution network.

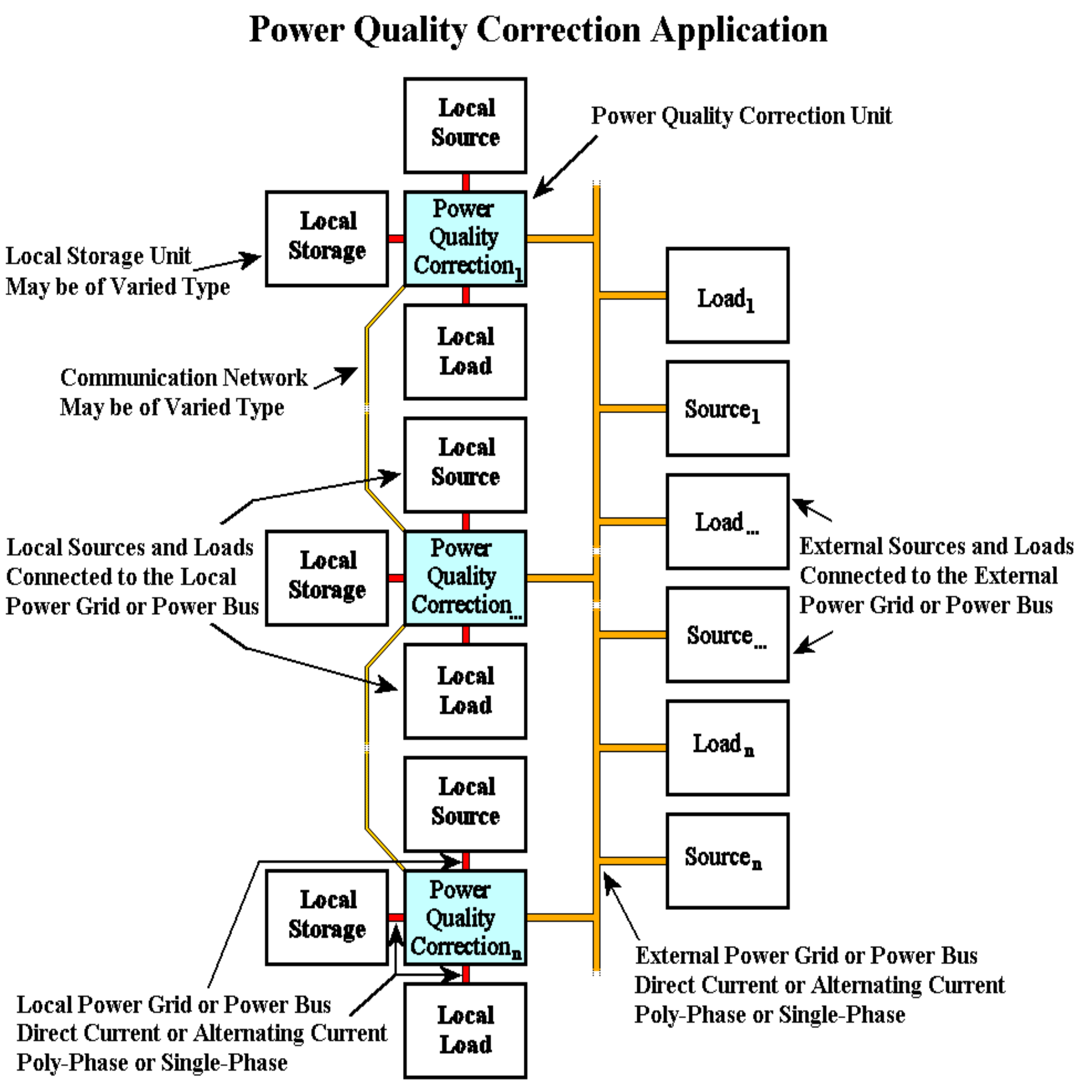


Figure 65. Power Quality Correction Application.

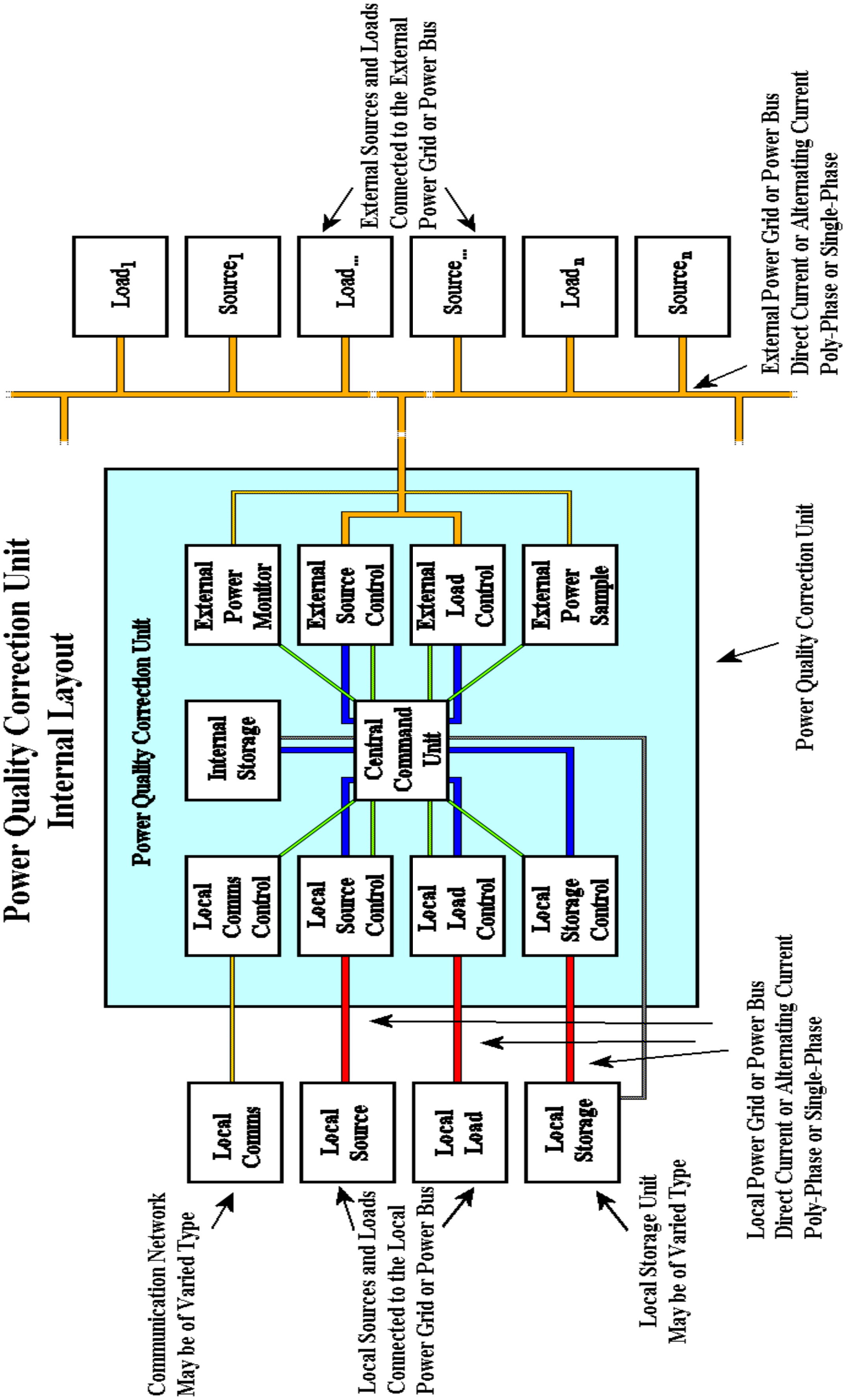


Figure 66. Power Quality Correction Unit.

10. CONCLUSIONS

10.1. Power Quality

Good power quality consists of stable frequency and voltage and low harmonic distortion. There are four main types of power quality disturbances; Voltage amplitude disturbances; Frequency disturbances; Phase relationship changes; and Waveform distortion. The origins and effects of power quality problems are very diverse and it is the user that has to ensure that their equipment can withstand, and also not cause, any power disturbances or reduce the power factor within the residential power distribution network.

10.2. Measuring Power Quality

While **displacement power factor** is commonly used when mainly linear loads are present, the most common indicators for non-linear loads are; **true power factor**, which takes into account both the phase shift and the wave-shape distortion; and **total harmonic distortion** which is a measure of the wave-shape distortion caused by non-linear loads.

10.3. New Zealand Residential Power Network

Linear loads stabilize networks and improve the network's power quality, while non-linear loads decrease power quality by introducing considerable harmonics into the already distorted New Zealand power distribution network. Non-linear loads also incur greater line losses and require larger power distribution equipment. Most of the existing load in New Zealand is still linear however, and the modern non-linear devices replacing them usually draw lower current, so the average national load power factor is still close to unity.

However, in **residential** New Zealand there is a move away from linear loads to more efficient non-linear loads, but this will decrease power quality and may increase total harmonic distortion above the 5% New Zealand limit.

The old 1960s mercury arc valve technology of Pole 1 within the DC link also injects high levels of background harmonic distortion into the New Zealand residential power distribution network, which is already weak having high impedance, making it sensitive to non-linear loads.

Due to the availability of low cost switch mode devices and the various national energy saving initiatives, it is getting harder to find linear loads in homes and although non-linear loads are more efficient than linear loads, the widespread adoption of high reliability, low cost, non-linear electronic products is decreasing the power quality by introducing harmonic distortion into the network, increasing total harmonic distortion over the 5% New Zealand limit and represents a possible source of faults and troubles for loads within the system.

10.4. Power Quality Standards and Regulations

The electricity supplier has the responsibility to maintain the quality of their supply within specified limits but it is the users that have to ensure that their equipment can withstand power disturbances, and it is also the user that must ensure their equipment does not cause any disturbances to the power distribution network. As utilities need larger wattage equipment to carry the extra current when power quality is low, most users' contracts state that they must maintain a power factor of greater than 0.95. Users who have moved to more energy efficient, but more power degrading, non-linear loads may be asked to pay a penalty or a higher rate for their electricity. In theory users may also be required to maintain their harmonic distortion at less than 5% as their loads must also comply with current harmonic requirements.

10.5. Non-linear Loads

The electronic front ends of non-linear loads make them more efficient than linear loads, but they are a common source of harmonics. A simple way of improving the non-linear loads power quality is to use passive filtering but this increases cost, physical size and weight. A more complex 'valley fill' front end further improves power quality, but adds more complication and cost to the final product. The most complex solution uses an active 'power factor correction' circuit which eliminates harmonic distortion, but adds the most cost to the final product.

Many of the loads being connected to the network today introduce significant harmonic distortion, and while the power of most of these devices is low, the increasingly large numbers of appliances with low harmonic angle diversity means that harmonic voltage levels are likely to rise in the future within the network. In particular, the very low harmonic angle diversity in CFLs suggests that multiple CFLs should be considered as a single high power load with correspondingly stricter harmonic requirements.

Measuring each individual load in the residential power distribution network requires us to intrude on each load separately to install complex hardware. A more effective option is to use simple hardware to measure at the point of common coupling and use sophisticated software to identify the complex dynamic signature of each load.

The proposed approach developed in this research identifies the distinct harmonic signature of each load, enabling differentiation between an almost infinite range of load signatures. No access to the individual loads is necessary and this provides a very convenient and effective method of gathering load data compared to traditional means of placing sensors on each of the individual components of the load. So, by a sophisticated analysis of the current of the total load, the software identifies the individual loads, and their daily time of use profile.

The resulting end-use load data is extremely valuable to consumers, energy auditors, utilities, public policy makers, and appliance manufacturers, for a broad range of purposes. A monitor placed at one point could determine how much energy goes into each of the major appliances within the home.

The most well known high quality local CFLs have a power factor of over 0.9 and low total harmonic distortion, but most manufacturers still use simple basic ballast circuits in their CFLs, mainly because of its lower cost. These low quality CFLs have several negative issues such as radio interference, high mercury level, premature failure, low power factor and high levels of harmonic distortion.

Harmonic addition with lamps of the same type are not linear and the interaction between low and high power factor lamps is complex. The addition of high power factor lamps partially cancels out the harmonics produced by low power factor lamps.

Besides complying with local safety and performance standards, CFLs are also expected to comply with local power quality standards. However a clause in the local standard means that CFLs only need to comply with the much more lenient requirements than other similar devices. Recently the local harmonics standard was amended to make the limits for CFLs more stringent, but this new clause is not called up in any local standard due to strong lobbying by the lighting industry.

10.6. Impact of Non-Linear Loads on Power Quality

Most modern electronic devices are non-linear and cause a number of disturbances within the network because they draw non-sinusoidal current. So, as these non-linear loads have increased, power quality has become an issue that cannot be ignored.

Harmonic distortion has significant effects on distribution equipment and can lead to increased costs due to increased maintenance, component failures or devices de-rating. Harmonics cause heating in cables, problems in switching circuitry and malfunctions in control systems; there could be false tripping, interference in ripple control and unstable, unpredictable operation in other systems. Other more subtle effects can lead to costly and unnecessary maintenance or equipment replacement.

All modern appliances are an issue when it comes to harmonics, but as they are used in multiples, and have a much less stringent harmonic requirement, the impact of CFLs needs to be more closely considered, especially within New Zealand's weaker, spread out power distribution network.

10.7. Locating Disturbing Loads

Trying to find such dispersed disturbances in the residential power network is difficult as most domestic meters do not measure power factor or harmonic distortion. These meters are however being replaced by 'smart' meters which are able to monitor domestic power quality.

As the effects of power quality disturbances can cause serious problems within a network, regulations and standards have been established to control power quality by introducing required limits. To comply with international power quality limits, product designers use power-factor correction and harmonic filter circuits. But no local regulations or standards refer to the more stringent local power quality standard which was specifically changed to match our local requirements. The author believes this is a mistake which will further weaken New Zealand's power distribution network.

10.8. MITIGATION

The two main issues which need to be addressed with regard to harmonics in New Zealand are; high background levels of harmonics; and high harmonic levels from non-linear loads in general and CFLs in particular.

The high background level of harmonic distortion is being addressed in part by the current upgrade to the HVDC link and by increased generation mid North Island. The long awaited upgrade to the High Voltage DC Link will not only strengthen the 'weak' New Zealand power distribution network, but also reduce the 'background' harmonic distortion currently injected into the network by the old 1960s mercury arc valve technology of Pole 1.

The high harmonic levels from non-linear loads in general and CFLs in particular are not easily addressed. Mitigation of the harmonic distortion caused by multiple small non-linear loads is very difficult once they are in the network due to the dispersed nature of these loads within the network.

Power quality correction devices can be retrofitted on large disturbing loads, but it is not as easy to retrofit them onto each small disturbing load, so they are usually installed at common connection points higher in the network. However the most cost effective way is to ensure that only high power quality non-linear loads are installed, as correcting the problem higher up in the network costs up to 10 times more than the cost of selecting high quality loads in the first place **[24]**.

Improving existing standards and regulations, and introducing new standards and regulations is only effective if they are actually implemented and complied with, so it is crucial that those who have oversight over the standards and regulations relating to power quality fully understanding the influence of non-linear loads on the power quality of the New Zealand low voltage electrical residential power distribution network. This research is expected to make the "decision makers" more aware of the issues around harmonics.

As part of this research, a power quality correction unit is proposed to reduce the distortions caused by non-linear loads as close to source as possible. The power quality correction unit is intended to be connected to non-linear loads, or at the first point of common coupling in the network. The unit corrects power distortions such as power factor, phase, frequency and harmonic distortion. The main benefit of this unit is improvement to the power quality of the local device it is connected to and also improves the power quality of the power distribution network so reduces the need to install expensive, large, power quality correction devices higher up in the network.

11. RECOMMENDATIONS

Wider investigations and mitigation initiatives are needed nationally, especially in areas where the residential power distribution network is the weakest, to quantify and qualify the extent of the influence of non-linear loads on the power quality of the New Zealand low voltage electrical residential power distribution network.

Utilities, manufacturers and policy makers need to monitor the power quality issue and work together to develop and/or review standards, focusing on power factor and harmonic distortion issues.

Regulators need also to ensure that they police energy using products to ensure that there is compliance with New Zealand's local specific power quality requirements, as local New Zealand requirements differ from the requirements of other first world countries, and even differ from Australia's power quality requirements. This is due not only to New Zealand's 'weak' power distribution network, but also to the already appreciable background harmonics levels created by New Zealand's unique, antiquated, DC link.

Intensive initiatives encouraging the use of non-linear loads should include harmonic filtering and power factor correction techniques, and/or consideration needs to be given to incentives to overcome the initial higher cost of higher quality non-linear loads.

This research is expected to provide a helpful source of information for future wider investigations and mitigation initiatives.

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13. APPENDIXES

A 1. AS/NZS 61000.3.2:2007

Proliferation of harmonic-producing equipment has been accompanied by a similar increase in research leading to improved understanding of the general harmonic problem, methods and techniques for studying it, and approaches for mitigating unacceptably high levels of distortion. The increased understanding of the problem has led to the development of standards that promote a shared responsibility between utilities and customers such that utilities are responsible for voltage quality and customers are responsible for not producing excessive harmonic currents. There two main standards commonly used.

Unlike the previous standard, AS/NZS 61000-3-2:2003, *"Limits for Harmonic Current Emissions (equipment input current <=16 A per phase)"* directly establishes harmonic current limits for each kind of equipments. Devices are classified in four groups: Class A (balanced three-phase equipment, household appliances, tools, dimmers for incandescent lamps, audio equipment), Class B (portable tools, arc welding equipment which is not professional equipment), Class C (lighting equipment) and Class D (all other equipments or personal computers and television receivers). For each class, the document advices harmonic current limits expressed in A, in A/W or in per cent of the fundamental.

A 2. AS/NZS 61000.3.2:2007 Amt A (31st October 2009)

Electromagnetic compatibility (EMC) Limits for harmonic current emissions

7.3 Limits for Class C equipment

c) Active input power >25 W

N/A**d) Active input power ≤25 W**

Discharge lighting equipment having an active input power smaller than or equal to 25 W shall comply with one of the following two sets of requirements:

- the harmonic currents shall not exceed the power-related limits of Table 3, column 2, or:
- the third harmonic current, expressed as a percentage of the fundamental current, shall not exceed 86 % and the fifth shall not exceed 61 %; moreover, the waveform of the input current shall be such that it begins to flow before or at 60°, has its last peak (if there are several peaks per half period) before or at 65° and does not stop flowing before 90°, where the zero crossing of the fundamental supply voltage is assumed to be at 0°.

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

  NOTE - Widespread use of devices meeting this criterion can cause interference in networks, particularly networks using ripple control signalling. It is intended to delete this second criterion from October 2010 subject to the outcome of a review to be carried out on the effect of the mass introduction of these lamps.

Notwithstanding the above, in New Zealand, for integrated compact fluorescent lamps (CFLIs) having an active power input in the range 14 W to 25 W (inclusive) the harmonic currents shall not exceed the power-related limits of Table 3, column 2.

NOTE - this requirement does not cover special purpose CFLIs such as Lusters, Candles and Fancies or reflector lamps.

Table 3 – Limits mainly for Class D equipment

NOTE - Refer to Clause 7.3b) for limits for Class C equipment

Harmonic order n	Maximum permissible harmonic current per watt mA/W	Maximum permissible harmonic current A
3	3,4	2,30
5	1,9	1,14
7	1,0	0,77
9	0,5	0,40
11	0,35	0,33
$13 \leq n \leq 39$ (odd harmonics only)	$\frac{3{,}85}{n}$	See Table 1

A 3. Fluke 43B

Fluke 43B power quality analyzer

The perfect tool for tracking down single-phase power-related problems

The 43B is the choice for diagnosing and troubleshooting power quality and general equipment failures. Easy to use thanks to menu selection of the power quality modes, it combines the capabilities of a power quality analyzer, a 20 MHz oscilloscope, a multimeter and a data recorder in a single instrument.

Power quality analyzer

- Measure power (W, VA, VAR) and power factor (PF, DPF)
- Calculate power and power factor on balanced 3-phase loads
- Measure voltage, current and power harmonics
- Measure dips and swells on a cycle-by-cycle basis for up to 24 hours
- Automatically capture up to 40 transients
- Measure motor inrush current and analyze using cursors
- Broad frequency range (10 to 400 Hz) for aviation, marine and railway applications
- Store up to 20 screens in memory

- *Watts, power factor, displacement power factor (cos φ), VA and VAR*
- *Voltage and current waveforms*

Oscilloscope

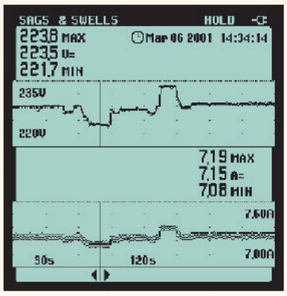
- Dual-channel, 20 MHz bandwidth digital oscilloscope
- 'Connect-and-view' automatic triggering for instant waveform display

Multimeter

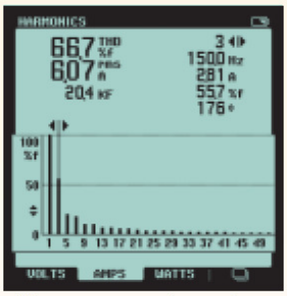
- Measure resistance, continuity and capacitance, and test diodes
- Measure temperature with optional temperature probe

Recorder

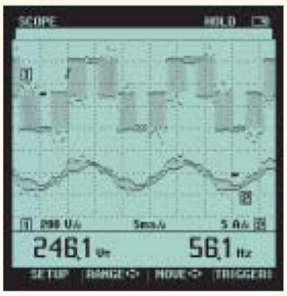
- Record 2 parameters for up to 16 days
- Record voltage, current, frequency, power, harmonics and all scope measurements
- Add cursors to analyze the trend



- *Continuously measure volts and amps on a cycle-by-cycle basis for up to 16 days*
- *Use cursors to read time and data of dips and swells*



- *Voltage, current and power harmonics*
- *Up to the 51st harmonics*
- *Total harmonic distortion*
- *Phase angle and individual harmonics*



- *Connect-and-View™ scope for quick waveform display*
- *View voltage and current channels simultaneously*

A 4. Electricity Regulations 1997

56 Quality of supply

(1) No person may use or continue to use any fittings or electrical appliance that unduly interferes with the satisfactory supply of electricity to any other person, or that impairs the safety of, or unduly interferes with the operation of, any fittings or electrical appliance.
(2) Compliance with ECP 36 is deemed to be compliance with subclause (1) , in respect of interference from harmonics.

ECP 36 means the New Zealand Electrical Code of Practice for Harmonic Levels (NZECP36:1993) **[10]** issued on 4 February 1993

A 5. Electricity (Safety) Regulations 2010

31 Requirements relating to quality of supply

(1) In order to preserve the quality of electricity supplied, the use of fittings and appliances must not unduly interfere with the satisfactory supply of electricity to any other person, or impair the safety, or interfere with the operation, of any other fittings or appliances.

(2) In relation to interference from harmonics, compliance with whichever of the following standards is applicable is deemed to be compliance with subclause (1) :

- (a) ECP 36:
- (b) IEC 61000–3–2:
- (c) IEC/TS 61000–3–4:
- (d) IEC 61000–3–12.

(3) In relation to interference from flicker, compliance with whichever of the following standards is applicable is deemed to be compliance with subclause (1) :

- (a) IEC 61000–3–3:
- (b) IEC/TS 61000–3–5:
- (c) IEC 61000–3–11.

(4) A person commits a grade B offence if he or she uses a fitting or appliance that breaches, or results in the breach of, subclause (1).

ECP 36: New Zealand Electrical Code of Practice for Harmonic Levels (NZECP36:1993) issued on 4 February 1993.

AS/NZS 61000.3.2:2007: Electromagnetic compatibility (EMC)—Limits—Limits for harmonic current emissions (equipment input current less than or equal to 16 amperes per phase): including Amendment 1.

IEC 61000-3-2 Ed 3.2: Electromagnetic compatibility (EMC)—Part 3-2: Limits—Limits for harmonic current emissions (equipment input current less than or equal to 16 amperes per phase): as amended by the deviation in IEC 61000-3-2:2007, including Amendment 1.

A 6. Equipment Classification

Because different types of loads draw current in different ways and so produces different harmonics that affect the power distribution network differently, equipment is grouped together into different classes, for the purpose of current harmonic limitations.

Class A consists of:

- balanced three-phase equipment
- household appliances, excluding equipment identified as class D
- tools, excluding portable tools
- dimmers for incandescent lamps
- audio equipment

Equipment not specified in one of the three other classes shall be considered as class A equipment

NOTE 1: Equipment that can be shown to have a significant effect on the supply system may be reclassified in a future edition of the standard. Factors to be taken into account include:

- number of pieces of equipment in use
- duration of use
- simultaneity of use
- power consumption
- harmonic spectrum, including phase

Class C

- lighting equipment

Class B

Equipment having a specified power less than or equal to 600 W, of the following types

- personal computers and personal computer monitors
- television receivers

NOTE 2: Class D limits are reserved for equipment that, by virtue of the factors listed in note 1, can be shown to have a pronounced effect on the public electricity supply system.

Class D

- portable tools
- arc welding equipment which is not professional equipment

A 7. Letter from David Ford - Chairman AS/NZS Standards Committee EL041-08

Sylvania Lighting Testing Laboratory

Where Innovation comes to Light!

Sylvania Lighting Australasia Pty Ltd
A.B.N. 81 000 534 243

Sylvania Way, Lisarow
(Locked Bag 9, Gosford)
NSW 2250 Australia
Telephone: +61 2 4328 0600
Facsimile: +61 2 4328 2605
www.sla.net.au

CFL's and Harmonics 15 October 2008

To: Peter Morfee
Ministry of Economic Development
PO Box 1473, Wellington 6140, New Zealand

Dear Peter,

Following the last EL 041-08 meeting in Wellington the committee asked me to write to you expressing their concerns on the issue of harmonics in the supply system. I have delayed this letter until after the second EL-034 meeting where the subject was discussed and the "International Conference on Harmonics and Power Quality" held last week in Woolongong. I am attaching relevant papers from that conference. Without going into too much detail the committees concern is:

When Replacing large amounts of incandescent lamps with CFL's

1 Dr Neville Watson's models predict harmonic problems for supply systems.
2 Australian Experts are not alarmed mainly due to points 3 and 4 below.
3 The model does not take into consideration Attenuation Effect due to distorted votage waveshape. See paper by Nassif. New paper by Dr Watson now considers this.
4 The model does not take into effect cancellations with different non-linear loads such as computers and TV's. See paper by Matvov.
5 Ashok Parsotam has readings at Aucklands Zone Substations showing continually increasing THD.
6 As yet Ashok has not processed this years readings.
7 NZ and some parts of Australia use 1050Hz for load control (21^{st} Harmonic). Whilst paper for 3 shows a reduction of this harmonic below model calculations and paper for 4 is ambiguous on this harmonic but predicts problems with calculated levels.

Conclusion

There is no such thing as a free lunch.

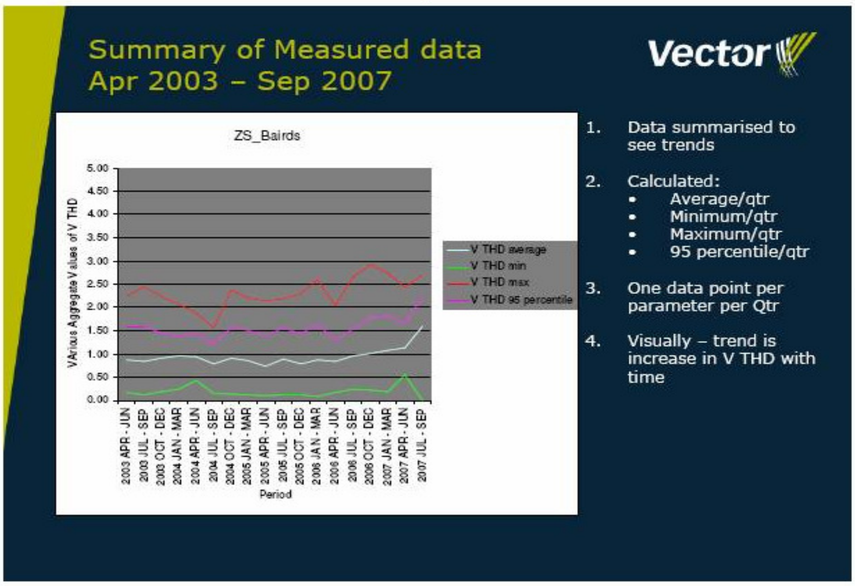
Savings in total power generated will be partially offset by Higher THD particularly 21st harmonic, higher Neutral currents and derating of LV/MV transformers in the network.

In Australia the Regulatory Impact Statement and cost incurred are based on normal CFL's that comply with International specifications (IEC61000-3-2). Discussions at two EL-034 meetings and with the Australian Energy Networks Association have indicated this is acceptable to the Australian supply networks at present. This will be reviewed in 2010.

In New Zealand some groups are concerned that IEC61000-3-2 is too leniant on CFL's below 26W and could lead to the graph below continuing to rise. However care should be taken that this could negate a valuable cancelling effect demonstrated in Point 4 above. That is, note the 5th and 7th Harmonics are reduced by the CFL waveshape being out of phase with the Computer and CRT waveshape. As 21 is a multiple of 7 use of improved CFL's could cause higher 21st Harmonic levels than with regular CFL's.

Naturally I leave it to you to draw your own conclusions regarding changes to standards and or regulations in New Zealand. This letter is intended only to draw your attention to committee concerns. Please try to aquire more recent supply sytem measurements before acting. Also if you see the need to regulate on harmonics emissions, look at all appliances not just the CFL because modifications to CFL's alone will not solve supply issues.

David Ford – Chairman AS/NZS Standards Committee EL041-08



A 8. E-Mail to David Ford from Peter Morfee - Ministry of Economic Development

From: Peter Morfee [mailto:Peter.Morfee@med.govt.nz]

Sent: Thursday, 16 October 2008 10:55 PM

To: davidford@sla.net.au

Subject: RE: Harmonics on the supply system

Thanks,

I have been in the harmonics game for many years. I designed and built NZ's first computer based harmonics measuring system. I was involved in extensive investigations in the NZ power supply network. I am also very familiar with the most sensitive electrical systems including medical electrical equipment.

I am known to look at harmonics as a kind of magic! I have seen significant even harmonics on NZ's power system. I have seen how the resonances of the system can move the problems around dramatically. Harmonics are something I feel comfortable with.

In my house I have a circuit where turning on a CFL operates a dimmer on another circuit causing it to ramp up and down until the CFL settles down.

I am also significantly involved in the development of international treaties and well familiar with the implications of the WTO etc.

As the top technical Regulatory advisor to the NZ government I am obliged to be satisfied that no regulatory issues, including both interference and safety issues, are likely it be encountered.

What is before me are a series of factors that I must take into account:

- The NZ supply network impedance is higher than that generally found in other comparable supply systems internationally. There are good reasons for this.
- NZ's supply system has a relatively high background harmonic distortion level. We have a lot of base load distorting equipment.
- NZ uses a significant amount of load control systems that can be interfered with by Harmonics.
- We have not adopted immunity control Standards, so we have no surety as to what levels of interference will become critical for equipment.
- NZ is pushing the introduction of CFLs earlier than many countries and already has a high penetration level.
- NZ appears to have a rapidly increasing harmonic distortion level in some locations.
- CFLs are given a relaxed level of harmonic restrictions by the applicable international Standard which contains two options for compliance.

So I am faced with the situation where we have a rapidly reducing harmonics "headroom" on our power system while we are implementing policies that increase the rate of installation of distorting equipment.

I recognise that the increasing distortion (pollution) is not simply a function of CFLs but they are one area where the rate of installation is being pushed to exceed normal market forces. The Government is a contributor to the rate of change!

I am therefore pushing ahead with a multi-pronged strategy which involves; Strengthening the existing regulatory system for all equipment by introducing formal recognition of the relevant IEC Standards as the expected (but not mandated) levels for all electrical equipment; Introducing more monitoring of compliance for products in the marketplace; and, Reviewing the applicable Standards for their adequacy for NZ.

In the later regard I have facilitated the review of 61000.3.2 and proposed that the relaxed limits be removed for NZ as they appear in my opinion to allow CFLs a disproportionate allowance for distortion.

Given this questioning of the recognised limits (without mandating), I have placed the decision making into the hands of the experts of the relevant Standards process to make a determination. The jury is now out considering their verdict!

I do not have evidence in my hands to support a regulatory intervention to overturn the decision of the Standards process, so, as long as the proper process is followed the end result will be the regulatory recognition of the resulting Standard, this approach has already been agreed as the policy position of the Government. We do not have any agreement to mandate the Standard nor to overrule it!

I suppose I have taken the role of debating the contrary and the industry the role of pro!

I have not suggested that the limits themselves be changed but that for the CFLs used for most common applications the more stringent limit be adopted.

The consideration process spans the Conference to allow the discussions there to have an influence on the outcome!

I must admit that I am nervous about CFLs for a number of reasons, but that comes from my assessment of the risks that they create. My work is focussed on addressing those risks in a manner that ensures that the end outcomes are satisfactory. The role of a modern regulator is to assess risk and to address it though the regulatory process. That is what I am doing.

I have a reputation in the Asian area as a leader in predictive risk assessment and professional regulatory processes. NZ as a result is looked at as a trusted professional leader. This reflects strongly on our ability to trade into Asia and underpinned the conclusion of the EEMRA which forms part of our FTA with China. It is therefore even important from a trade perspective that NZ looks carefully into all the issues around the introduction of CFLs.

I thank you for your input and urge you to work with the process to get the best results for both our countries, as I am convinced that if there is indeed a problem with CFLs in any regards, Australia, as a partner in the early promotion of these technologies, will not have a lot of time to take action.

I trust that this assist you to understand where I am coming from in this area of work.

I personally feel that we are pushing the lighting industry to it's limits to address some of the quirks of this "new" technology, and given the peculiar things that I have encountered, I think we have yet to get to grips with tricks that this magic has up it's sleeve.

One of my current tasks is to document the peculiarities and how they can be addressed. To identify where CFLs are not suitable and where they will misbehave, so that this information can be readily promulgated to the users if they are perceived to be safety issues.

Please feel free to make comment on these points and to distribute these comments to your committee.

In closing let me thank you for your contribution to the Standards process, it not easy taking on the role of a chairman.

Regards..

Peter Morfee *B.E. (Elect) M.E. (Mech)*| Principal Technical Advisor | Energy Safety
Ministry of Economic Development

PO Box 1473, Wellington 6140, New Zealand