THE IMPACT OF ENERGY EFFICIENT LIGHTING ON POWER NETWORKS

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DECLARATION - PLAGIARISM

As the candidate's Supervisor, I agree/~~do not agree~~ to the submission of this dissertation.

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ABSTRACT [1], [2]

The power utilities in many countries have come under stress as a result of generation capacity deficits, looming fuel costs and in many developing countries the electricity demand is very quickly outstripping the available electricity supply [1]. Since 2006, Eskom has been utilizing large scale residential efficient lighting roll out programmes as a cost effective short to medium term supply security solution while the longer term capital intensive supply side, “Build Programme” was underway [2]. This mostly involved the use of non-linear compact fluorescent lamps (CFLs) to replace linear incandescent lights (ILs) with very little involvement and influence by the utility QOS (quality of supply) engineers that are responsible for ensuring supply quality on the specifically targeted Distribution networks. This dissertation highlights that while CFLs can provide the desired energy or peak power reduction required, they can also have an impact on QOS within specific sensitive networks if the appropriate CFL standards (i.e. IEC 61000-3-2) minimum requirements are not adhered for both power factor and harmonics.

These large scale CFL implementations have cost implications and hence metering and verification methods and models have been developed to simulate and quantify the returns from investing in energy efficient lighting initiatives. CFL manufacturers differ on ballast designs which have a direct impact on lamp efficacy, harmonic distortion and power factor which contribute to network quality of supply. It is for this reason that this dissertation raises an awareness of the importance of appropriate CFL standards i.t.o. the impact on quality of supply from a harmonics and power factor perspective. Due to the lack of more recent available or reliable sources of CFL test data, laboratory investigations were used to confirm the harmonics and PF characteristics of a variety of commercially available CFLs in addition to those utilised in previous large scale rollout programmes. The harmonics and power factor performance measured were compared for compliance against the international limits as prescribed in IEC 61000-3-2. Further investigations on international lighting industry standards for CFL’s has revealed gaps pertaining to harmonics and PF limits. This study is concluded by highlighting the impact of CFLs on power networks. It also provides a brief guide for utility power quality engineers by imparting an understanding of their role for the large scale efficient lighting programmes in order to pro-actively contain any possible impact on quality of supply within the regulatory limits as prescribed in the QOS standards.

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NOMENCLATURE

Abbreviations

ANSI	American National Standards Institute
CFL	Compact Florescent Lamp
EEDSM	Energy Efficiency and Demand Side Management
FTL	Flourescent Tube Lamps
GLS	General Lighting System (referenced interchangeably with 'IL')
HPF	High Power Factor
IL	Incandescent Lighting (referenced interchangeably with 'GLS')
ISO	International Standards Organisation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LV	Low Voltage
LPF	Low Power Factor
PF	Power Factor
PLC	Programmable Logic Controllers
QOS	Quality of Supply
ROHS	Regulation on Health Standard (EU standard)
THD	Total Harmonic Distortion

Units

kVA	kiloVolt Amp (1000 units of apparent power)
kVAr	kiloVAr (1000 units of reactive power)
kW	kiloWatt (1000 units of real power)
kWh	kiloWatt Hour (1 unit of electricity)
GWh	gigaWatt Hours (10^9 watt hours)
Lm	Lumens
mA	milliAmp
MV	Medium Voltage
MW	MegaWatt (1000 units of power)
MWh	MegaWatt Hour (1000 units of electricity)
V	Volt
VA	VoltAmp (1 unit of apparent power)

Symbols

I	current

Subscripts

i	current (typically used with reference to THD)
n	Harmonic Order (used interchangeably with ‘ν’ in reference material)
ν	Harmonic Order (used interchangeably with ‘n’ in reference material)
v	voltage (typically used with reference to THD)

CHAPTER 1: INTRODUCTION [3], [4], [5]-[9]

1.1 Background [3], [4]

The recent global rising of energy costs, looming public concern about the environmental impact of energy use, and the utility energy constraints have increased the relevance and importance of energy efficiency, energy management and energy conservation with the planets diminishing energy resources [3].

Since 2006, Eskom like many utilities globally have successfully utilized residential efficient lighting retrofits to achieve EEDSM targets required to provide security of supply in the short to medium term [4]. Eskom managed to successfully implement large scale efficient lighting rollouts in short spaces of time to alleviate generation constraints i.e. 5.5 million CFLs during Western Cape power crisis in 2006, 4.4 million CFLs during transmission constraints in 2007, 16.8 million CFLs during national generation capacity constraints in 2008 and more recently a further 32 million CFLs without a sufficient understanding of the impact on specific networks. A total of 64.4 million CFLs (cumulative savings of 1511 GWh/annum, 2008.48 MW) rolled out in the country since 2005 through various strategies with little influence by the utility network QOS engineers that are responsible for ensuring supply quality on the specific targeted Distribution networks.

This dissertation highlights that while CFLs can provide the desired energy or peak power reduction, it can also have an impact on the power quality of a specific sensitive network if the appropriate CFL standards as per IEC 61000-3-2 minimum requirements pertaining to both power factor and harmonics are not being adhered to especially when CFLs are procured for large scale rollout programs.

1.2 Importance of the Research [5]-[9]

Considering that CFLs are being deployed on power networks through large scale energy efficiency programmes globally, this study addresses the following 2 research questions :-

1. How will large scale CFL deployment negatively impact power quality on specific networks ?
2. If this is so, then what can be done to mitigate the negative impact on power quality ?

This study will therefore add value to utility network engineers responsible for supply quality within both Eskom and local municipalities in that they would be able to use the critical information provided to assess and influence the negative impact of replacing the original incandescent lighting linear loads (100% original load) with reduced CFL non-linear loads (20% of original incandescent load) prior to the large scale CFL rollout programmes within specific networks.

This study will also assist in highlighting to the lighting industry and manufacturers the need for appropriate CFL ballast specifications and standards in order to contain any possible impact on power quality within the regulatory limits as prescribed in the QOS standards i.e. IEC 61000-3-2, IEEE 519-1992, NRS048-2:2007 and IEC 61000-3-6. [5]-[9]

1.3 Aim of the Research

The main objective of this dissertation is to answer the research questions posed above. This will be achieved if the following specific objectives are addressed :-

1. Establish if the CFL standards currently utilised are adequate enough to mitigate the negative impact on power quality which more specifically relates to harmonics.
2. Identify appropriate international harmonics standards that are applicable to mitigate the negative impact on power quality.
3. Conduct laboratory tests to establish whether the commercially available CFLs meet the standards required to minimise the negative impact on power quality.
4. Review relevant literature and case studies to establish the impact of large scale CFL deployment on power quality.
5. Establish the role of utility power quality engineers in mitigating the negative impact of large scale CFL deployment on power quality.

1.4 Hypothesis

If the penetration of CFLs on the power networks are increased without adherence to appropriate standards like IEC61000-3-2 then power quality could be adversely impacted because of the uncontrolled increase in harmonic levels. To mitigate any adverse impact on power quality would require the deployment of appropriate standards for CFLs and a more proactive role of the power quality engineers in large scale CFL programmes.

1.5 Research Problem / Statement

Global utilities and electricity distributors like Eskom utilise large scale CFL programmes to address energy constraints. These CFLs like those commercially available have specifications that primarily focusses on efficiency, aesthetics and environmental parameters but very importantly neglect to give attention to the technical parameters that will have an influence on power quality w.r.t. power factor and harmonics. Often the reason for these inadequate CFL standards are as a result of the absence of involvement of the utility power quality engineers in the large scale CFL programmes.

This research holistically evaluates the impact of CFLs on a network power quality with the intention of identifying the deficiencies in the lighting industry's technical specifications and standards currently utilized for the CFLs procured for the large scale rollout programmes. This study will provide a guide to network engineers, empowering them to be instrumental in large scale efficient lighting programmes especially on certain networks with existing power quality issues. This study will also raise awareness within the lighting industry and manufacturers to also adopt relevant technical specifications that ensures compliance to acceptable limits for harmonics and power factor.

1.6 Delimitations

This research study will be limited as follows :

- Application of CFLs (compact florescent lamps) as an efficient lighting technology,
- Understanding the technical performance of local commercially available CFLs and their interaction with a few other load types in laboratory conditions,
- Case studies and simulation based mostly on global network conditions.

1.7 Outline of Chapters

Chapter 1 is an introduction to the research content. It provides the background on the importance of CFLs in achieving energy efficiency objectives in addressing power constraints, and how the inherent characteristics of these devices can also adversely impact quality of supply on the specific networks if not applied correctly.

Chapter 2 highlights the literature review. This includes an introduction to the importance of energy efficiency, QOS, CFL characteristics and standards in the current context. It also highlights the gaps in technical specifications relating to power quality with CFL standards applied by the lighting industry.

Chapter 3 covers how the laboratory investigations and modelling exercises conducted, to confirm the inherent non-linear qualities of CFLs that may have an adverse impact on the network if not applied correctly.

Chapter 4 covers an understanding and analysis of global field studies conducted and models developed to highlight the impact of CFLs on the network through review of field studies including actual physical network measurements.

Chapter 5 covers the analysis and discussion of the research leading to the guidelines for utility network QOS engineers to play a more meaningful role in future large scale CFL programmes.

Chapter 6 is the deduced conclusion from analysis of laboratory results, and literature reviewed in this dissertation.

Chapter 7 is the recommendation on further work required from analysis and conclusion.

Reference section lists the literature reviewed and further relevant reading pertaining to the topic.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

For this dissertation, the literature reviewed is based on a discourse of the impact of efficient lighting (CFLs) on power networks. From this foundation, three key threads of arguments are extracted. The first relates to the understanding of the importance and need for energy efficiency through large scale efficient lighting (CFLs) rollouts as a short to medium term low cost quick fix solution to the power crisis in both the global and local South African context. The second argument relates to the importance of power quality on a distribution network. Lastly, providing an understanding of CFLs non-linear characteristics and standards which if not managed could have an adverse impact on the network power quality. As highlighted in figure 2-1, these perspectives are threaded together to argue respectively, in this dissertation, that CFLs can achieve both the desired quick fix energy efficiency benefit by meeting the specified energy efficiency standards but could also have minimal adverse impact to power quality within specific networks if appropriate technical performance standards are applied and met.

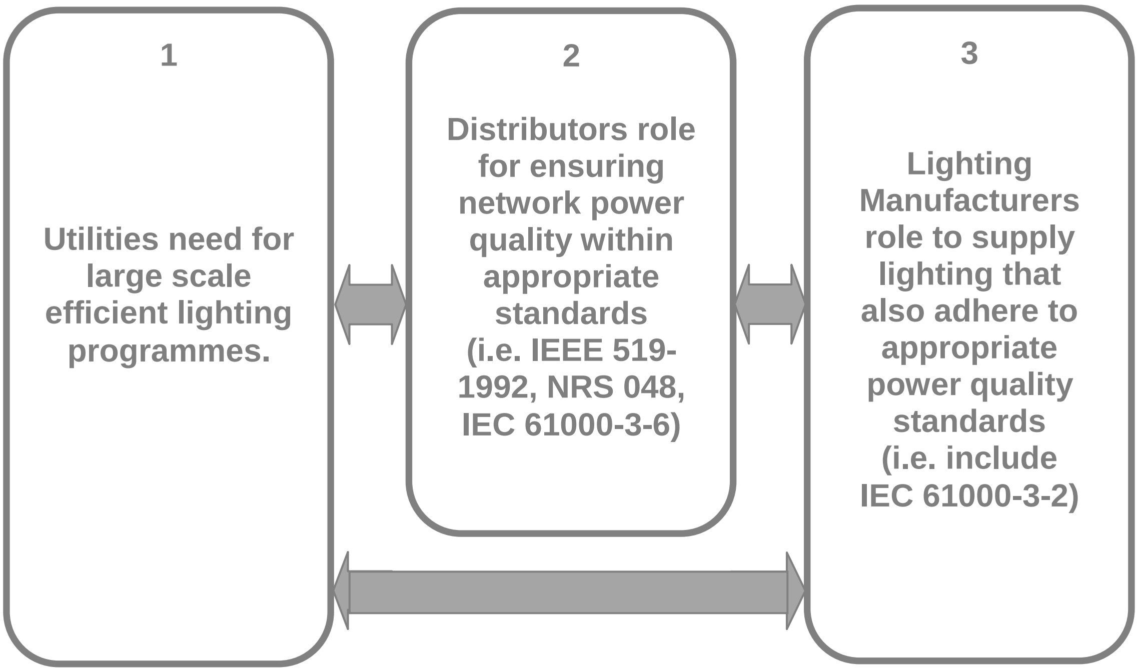


Figure 2-1 Finding a Balance with CFL Performance and Specifications

Although not covered in this dissertation, managing environmental impact is also very a crucial consideration for any engineering project or solution, and more so because of the CFL mercury content. While ROHS prescribes mercury content for CFLs, handling and disposal of CFLs must be considered in the holistic lifecycle of CFLs in large scale implementation programmes.

2.2 Need for Large Scale Efficient Lighting Programmes, [1], [10], [11], [12]

Global utilities as is the case in Africa are exposed to the risk of hindering government's objectives for economic development and improving of the quality of life with the eminent power constraints and inefficient energy usage. In addition to economic growth there are other drivers for energy efficiency which include the shortages of fossil fuel reserves for future power generation. In developing countries like Africa, additional power generation capacity can take several years to start and complete construction because of factors relating to financing, civil strife and drought that has to be resolved first. [10], [11]

Despite the global concerns and call for support on matters relating to climate change and environmental preservation, alternative low carbon or renewable energy solutions (including the recently discovered shale gas deposits in South Africa) will take another decade before being in a position to start displacing base load fossil fuel power capacity. Research indicates that energy efficiency remains the most cost effective short to medium term interim solution. [10], [11]

The widespread inefficient use of lighting more specifically within the residential market being a significant contributor to both energy and peak power demand and hence making it an ideal target market for demand-side and energy efficiency opportunities. Utilities large scale energy efficiency programmes make efficient lighting technologies on offer a win-win solution for all stakeholders. At a national level, these programmes would improve the national energy security and release up some generation capacity so desired thereby minimising the demand for fossil fuels, that are sensitive to price fluctuations and availability. Energy efficiency initiatives like these provide financial benefits that are not only substantial to the consumers but also the utility and government while the environmental impact from energy consumption is minimised as illustrated in table 2-1. [1]

Table 2-1 Benefits of Large Scale Energy Efficient Lighting, [1]

Customers	Reduction in energy and energy bill, mitigation of impacts of higher tariffs
Utilities	Reduction of peak load, capital needs and cost of supplying electricity
Governments	Reduction of fiscal deficits, public expenditures and improved energy security
Environment	Reduced local pollution and in Greenhouse Gas (GHG) emissions

Most developing countries still rely on the 100-year-old incandescent lighting technology. However, over the last several decades there have been major technological innovations with lighting. Figure 2.2 illustrates how the lighting efficiency or rather efficacy (lumens/watt) has evolved with improvements since their commercial viability in the early eighties. The figure below (see Figure 2.3) depicts the evolution with the many different efficient lighting technologies that offer energy saving potential for a variety of lighting applications. High quality CFLs still are the most attractive lighting option for the replacement of ILs in developing countries seeking quick peak load reductions which also provide benefits for the consumers, utilities, governments, and the environment as highlighted in Table 2-1. [1]

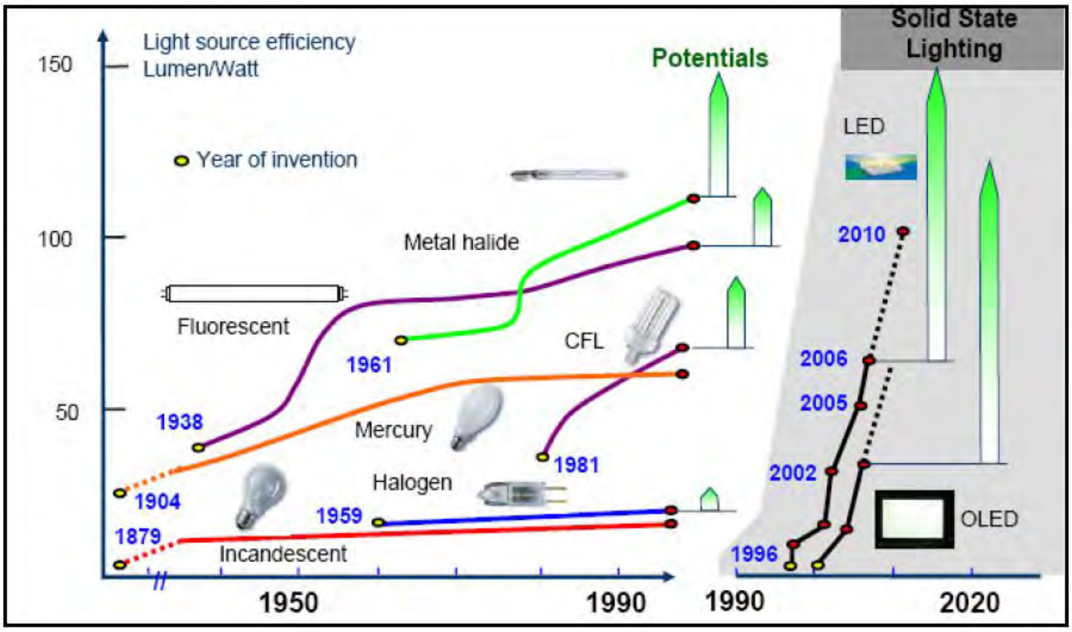
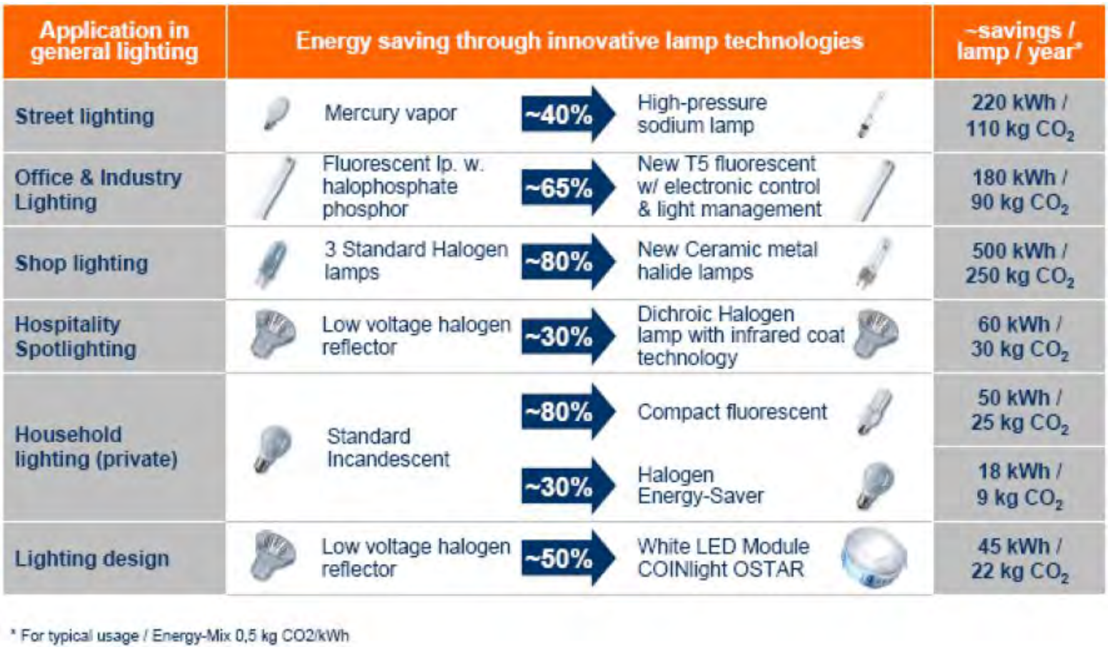


Figure 2-2 Improvements in Lighting Technologies, [1]



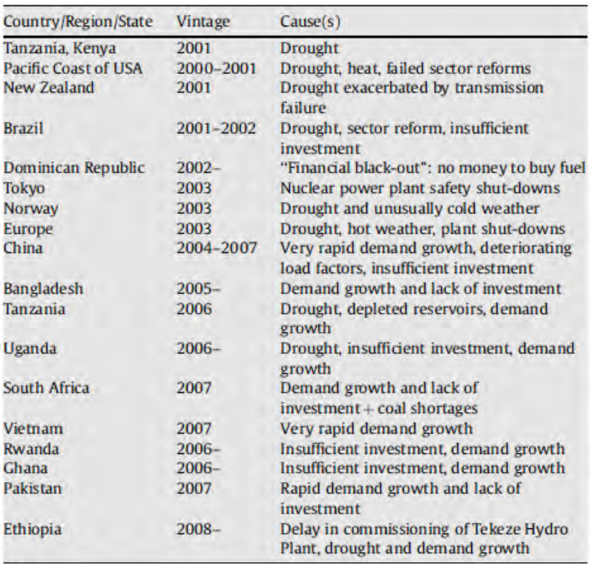
Application in general lighting	Energy saving through innovative lamp technologies			~savings / lamp / year*
Street lighting	Mercury vapor	~40%	High-pressure sodium lamp	220 kWh / 110 kg CO_2
Office & Industry Lighting	Fluorescent lp. w. halophosphate phosphor	~65%	New T5 fluorescent w/ electronic control & light management	180 kWh / 90 kg CO_2
Shop lighting	3 Standard Halogen lamps	~80%	New Ceramic metal halide lamps	500 kWh / 250 kg CO_2
Hospitality Spotlighting	Low voltage halogen reflector	~30%	Dichroic Halogen lamp with infrared coat technology	60 kWh / 30 kg CO_2
Household lighting (private)	Standard Incandescent	~80%	Compact fluorescent	50 kWh / 25 kg CO_2
		~30%	Halogen Energy-Saver	18 kWh / 9 kg CO_2
Lighting design	Low voltage halogen reflector	~50%	White LED Module COINlight OSTAR	45 kWh / 22 kg CO_2

* For typical usage / Energy-Mix 0,5 kg CO2/kWh

Figure 2-3 Energy Savings through Innovative Lighting, [1]

To appreciate the critical role of CFLs to utilities, one needs to appreciate the global context of the Power Crisis. Since the new millennium, an increase power crisis in both developing and developed countries are depicted in Table 2.2.

Table 2-2 Notable Power Shortages since 2000 – developed and developing economies, [12]

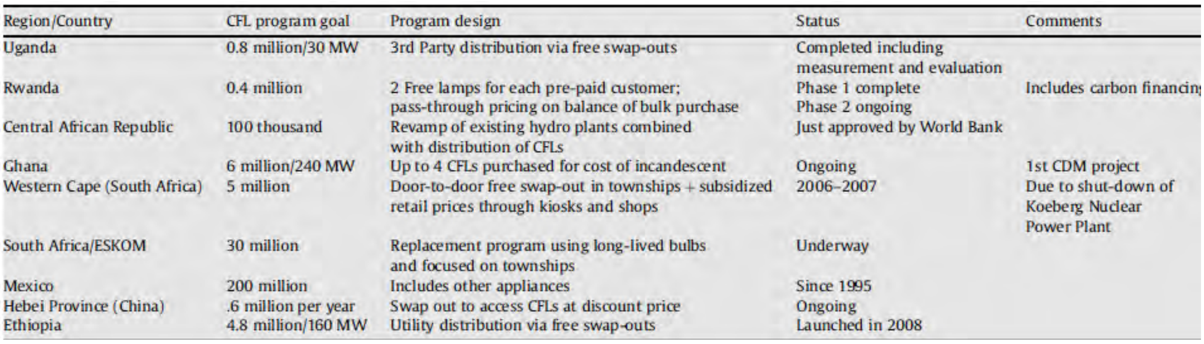


Country/Region/State	Vintage	Cause(s)
Tanzania, Kenya	2001	Drought
Pacific Coast of USA	2000–2001	Drought, heat, failed sector reforms
New Zealand	2001	Drought exacerbated by transmission failure
Brazil	2001–2002	Drought, sector reform, insufficient investment
Dominican Republic	2002–	"Financial black-out": no money to buy fuel
Tokyo	2003	Nuclear power plant safety shut-downs
Norway	2003	Drought and unusually cold weather
Europe	2003	Drought, hot weather, plant shut-downs
China	2004–2007	Very rapid demand growth, deteriorating load factors, insufficient investment
Bangladesh	2005–	Demand growth and lack of investment
Tanzania	2006	Drought, depleted reservoirs, demand growth
Uganda	2006–	Drought, insufficient investment, demand growth
South Africa	2007	Demand growth and lack of investment + coal shortages
Vietnam	2007	Very rapid demand growth
Rwanda	2006–	Insufficient investment, demand growth
Ghana	2006–	Insufficient investment, demand growth
Pakistan	2007	Rapid demand growth and lack of investment
Ethiopia	2008–	Delay in commissioning of Tekeze Hydro Plant, drought and demand growth

Global power shortages are characterised firstly by underinvestment followed by accelerated peak demand growth that erodes the utilities reserve margins to under the minimal acceptable threshold, and a national power crisis is then realised by a combination of unfavourable factors including weather, fuel supply, or plant availability. Unfortunately, in most cases, the required investment decisions are not made or possible until the actual widespread shortage effects are experienced. The delays with implementing urgent investment decisions required for either bringing on new supply side and/or demand side solutions often further extend the length of the power crisis resulting in an adverse national impact on quality of life and the national economy. This situation requires a very effective phasing in of a power crisis recovery strategy to immediately mitigate the impact at the start of the power crisis while long term solutions are developing. [12]

In general, power shortages may vary in both the nature and length and hence no single solution for all cases. In many cases, solutions like sensible rationing programmes and large scale CFL replacement programmes have shown to be effective to the various types of power shortages. An integrated approach to the supply–demand suite of solutions is most effective with a portfolio typically consisting of : i) a sensible mixed market based rationing, ii) emergency mobilizing of customers generation capability, iii) contracted interruptible customers, iv) customer load control, and v) large scale energy efficient lighting programmes. Large scale CFL replacement programmes are found to be most effective in most cases by yielding quick turn around and effective load reduction results. In addition to this the above mentioned suite of solutions, social networks should also be deployed as a safety net for the power crisis. Large scale CFL programmes targeting the poor households remain attractive as it provides both a reduction of the household consumption and electricity bill as shown in Table 2-3. [12]

Table 2-3 Some Indicative Bulk CFL Programs in Developing Countries, [12]



Region/Country	CFL program goal	Program design	Status	Comments
Uganda	0.8 million/30 MW	3rd Party distribution via free swap-outs	Completed including measurement and evaluation	
Rwanda	0.4 million	2 Free lamps for each pre-paid customer; pass-through pricing on balance of bulk purchase	Phase 1 complete Phase 2 ongoing	Includes carbon financin
Central African Republic	100 thousand	Revamp of existing hydro plants combined with distribution of CFLs	Just approved by World Bank	
Ghana	6 million/240 MW	Up to 4 CFLs purchased for cost of incandescent	Ongoing	1st CDM project
Western Cape (South Africa)	5 million	Door-to-door free swap-out in townships + subsidized retail prices through kiosks and shops	2006–2007	Due to shut-down of Koeberg Nuclear Power Plant
South Africa/ESKOM	30 million	Replacement program using long-lived bulbs and focused on townships	Underway	
Mexico	200 million	Includes other appliances	Since 1995	
Hebei Province (China)	.6 million per year	Swap out to access CFLs at discount price	Ongoing	
Ethiopia	4.8 million/160 MW	Utility distribution via free swap-outs	Launched in 2008	

A multi-stakeholder task team was established as a South African national response to electricity shortage that was observed with unprecedented levels of load shedding nationally at the start of 2008. As a last resort measure in an attempt to avoid the collapse of the of the national electricity supply system, load shedding has been deployed to immediately restore the shortage of generation capacity. There has been numerous interventions prior to the deployment of load shedding as the last option to reduce power demanded in an emergency situation. Given the capacity availability, demand forecast and the suite of short to medium term supply and demand solutions highlighted, the risk of load shedding was expected to remain high during planned maintenance periods until arrival of new base load power stations.

A suite of planned interventions are required to mitigate the risk of load shedding in the period leading up to the arrival of new peaking and base load generation stations on the grid. There were large scale efficient lighting programmes deployed nationally to replace the use of inefficient incandescent lighting in both domestic and commercial sectors. The CFL provided the same lighting level whilst consuming less than 50% of the power required by incandescent lighting. The in excess of 10 million lower income homes electrified under governments electrification programme in South Africa, conservatively represent 600MW (i.e. minimum 4 lamps per household) savings by replacing with CFL's on a free basis. This programme was projected to save 750 MW by 2010 and was intended to accommodate free exchange to lower income households until 2015.

Section Conclusion : Globally CFLs play a very crucial shorter to medium term role as a demand side solution required to address the power crisis. Since 2005, South Africa’s power utility, Eskom, has also been utilizing large scale residential efficient lighting retrofits to achieve DSM targets and also address generation capacity constraints. A total of 64.4 million CFLs rolled out in the country since 2005 through various large scale programmes but with little involvement or influence by the utility power quality engineers responsible for ensuring supply quality within the specific targeted Distribution networks.

2.3 Why is Quality of Supply Necessary ? [15], [16], [17]

Power quality is a set of standards with limits prescribed to ensure that power systems function in a safe manner with optimal performance and lifespan. Lifespan and return on assets becomes critical when it is dependent on funding through tariffs that are regulated like in South Africa. It broadly defines the electrical power driving an electrical device and it also defines the device's ability to operate correctly with that electric power. The absence of quality power may result in an electrical load (device) malfunctioning, failing prematurely or merely not operate. The many cases and causes for poor quality of electric power. The electricity industry is made up of the power generation business, power transmission business and ultimately electricity distribution business that distributes power directly to an end user customers load through the electricity meter located on the customer's premises.

Electricity travels through the customers internal reticulation (wiring) to the equipment (load). The movement of electricity from the generators to the end users equipment is complex and also further compounded with the unfavourable changes in weather, generation, demand amongst other factors that could compromise the quality of power. Power quality is a broad term that refers to the quality of the mains voltage supply rather than the mains current or power. The term power makes reference to the energy flow and also the current that is demanded by a load which is mostly uncontrollable.

Often power quality is broadly defined with reference to a set of supply parameters that include:

- the voltage magnitude variations,
- the voltage and current transients,
- the service continuity,
- and the supply's waveform harmonic content.

Another perspective is to view quality of power as a compatibility issue between either :

- the electrical load/s (or equipment) on a grid with the grid event itself,
- or the grid's power delivered (and events) with the load (or equipment) connected.

As discussed further in chapter 5.4, the CFL compatibility issues can be resolved either by :

- making the equipment standards tougher (i.e. in the case ensuring the CFLs compliance to IEC 61000.3.2),
- limiting the penetration volumes of CFLs upfront within sensitive networks,
- cleaning the power (i.e. in this case by either grid strengthening or harmonic filtering).

Ideally, in South Africa, power quality for an electrical distribution system refers to the extent to which the mains voltage supplied is a sinusoidal waveform at 50Hz having a constant amplitude of 230V.

Practically speaking, the utility mains power source is not actually ideal as they deviate from a pure sine wave. Both the utility generators and/or distribution systems can have severe power quality issues with voltage drops or transients whereby both could adversely impact of electrical equipment (loads). High levels of voltage distortion in a power system can also be harmful to electrical equipment. Unlike the case for either voltage drops or transients, distortion is most often caused by non-linear electric equipment (like CFLs) operating in the system. The term power quality, for a non-linear electric equipment (device) refers to the extent to which this equipment distort the voltage waveform and also shifts voltage and current phase relationship.

The power quality characteristics of incandescent lighting systems are resistive linear in that it causes neither supply voltage distortion nor does it affect the voltage and current phase relationship. Non-linear lighting (i.e. low voltage IL, high intensity discharge and fluorescent) utilising ballasts or transformers often distort the waveform for current. This short bursts of current drawn by non-linear devices distort and may alter the phase relationship with the voltage. While the reactive power of these non-linear devices affect the power factor which is also a power quality concern as the distribution network must provide for this reactive power.

Section Conclusion : Power quality is necessary to ensure that an electrical load do not malfunction intermittently, fail prematurely or not operate at all. These power quality issues may each have a unique cause i.e. maybe resulting from sharing of the same electrical infrastructure whereby issues on one customer’s premises cause transients that may affect all the other customers sharing the electrical subsystem. Power quality issues like harmonics from within a customer’s own reticulation may or may not affect other customers on the same network. Non-linear devices like CFLs generate large amounts of harmonic currents which can cause detrimental effects such as overheating of conductors, energy losses and mechanical stress on the power distribution system. Harmonic issues can be managed with a premium robust network design and also well proven strategically positioned harmonic reduction equipment. To reduce impact on power quality some CFL manufacturers have integrated filters to reduce current distortion in the electronic ballast CFLs. In regulated markets when electricity tariff increases reaches tipping point concerning consumer affordability, effective management of supply quality will ensure optimal life-cycle and returns of power system assets that is very dependent on regulated funding.

2.4 What are the QOS Standards for Harmonics ? [5], [6], [8], [9], [13], [14]

It is important to have a global perspective of electrical equipment standards w.r.t. harmonic levels especially now considering the global large scale roll out programmes of non-linear energy efficient domestic lighting like CFLs. There are many standards applied around the world and it is a good exercise to benchmark our practices against global standards. The voltage-distortion problem (i.e. deviating from a pure sine wave of supply voltage) should now increase from large scale deployment of non-linear devices (i.e. equipment containing power electronics like rectifiers). The last decade has been noted with considerable effort towards providing recommendations for harmonic limits through international standards and harmonisation. These standards are intended to provide customers with protection from the possible effects of poor voltage, by prescribing supply voltage limitations for the total harmonic distortion and the individual harmonics. [14]

2.4.1 Harmonic Current Limits for Electrical Equipment

ANSI (American National Standards Institute) :

Equipment manufacturers and end users are expected to comply with the supply utility's standards and controls for magnitude of emitted harmonics. For commercial electronic ballast lighting systems, ANSI Standard C82 sets current harmonic limits for the **total harmonic distortion (THD) at 32% and for the higher amplitude harmonics limited to 7%** of the fundamental current. Most American power utilities (like Duke Power and New England Electric Systems) would restrict their large scale programmes to electronic ballasts with THD of less than 20%. [13]

Australian / New Zealand (Adoption of IEC 61000-3-2 standard) :

AS/NZS 61000-3-2:2003 is an Australian / New Zealand standard relating to harmonic current emissions for electrical equipment that draw under 16 Amps per phase which supersede the AS3134 standard. This is an adoption of IEC standard IEC 61000-3-2 which states that CFLs are identified as class C lighting equipment drawing power that is larger than 25 W are expected to comply to more stringent limits for higher harmonics than equipment drawing power under 25 W. The standard also highlights that class C equipment with input power up to and including 25 W should comply to the harmonic limits of class D (as in Table 2-4 below). Limits for class D equipment as shown on Table 2-4 specifies that discharge lighting equipment should adhere to at least either of the following harmonic limits :

- the current harmonics to comply to the power related restrictions as shown in column 2 of Table 2-4,
- or alternatively, the third harmonic be restricted to 86% and the fifth harmonic to 61% of the fundamental current. In addition to this, the current drawn shall commence flow not later than 60°, have its last peak not later than 65° and continue flow not beyond 90°, and where the fundamental voltage's zero crossing will be at 0°. [14]

Table 2-4 IEC 61000.3.2 Limits for Class D Equipment (equipment ≤ 25W), [6]

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 ≤ n ≤ 39 (odd harmonics only)	3.85/n	Refer to Class A Limits

IEC (International Electro-technical Commission) :

The International Electro-technical Commission (IEC) prescribes limits for lighting equipment in the form of **PF greater than 0.96** and **THD under 33%.** Further to this, the IEC standards for lighting makes an exception for lighting equipment that is rated for power under **25W**, such as screw-base CFLs. It should also be noted that, the **IEC 61000-3-2** standards also provide protection to the utilities network equipment by restricting too high current harmonics generated from the customer's load.

The IEC 61000-3-2:1998 standard expresses the maximum current emission limitations with the ratio of current to lamp wattage (i.e. measured in mA/W) for lamps rated to be equal to and under 25 W, were adopted as reflected under the 2nd column of Table 2-5. The third column of the table show the current (I rms) for the vth harmonic current in terms of the fundamental current ($I1$ rms), was established using the second column of the table where the fundamental harmonic current measured as a ratio of voltage (i.e. the adopted voltage of 230V) to the active power (W). [14]

Table 2-5 CFLs Harmonic current limits according to IEC 61000.3.2, [6]

Harmonic order ν	Maximum permissible harmonic current per watt (mA/W)	Maximum permissible harmonic current in % of fundamental
3	3.4	78.2
5	1.9	43.7
7	1.0	23
9	0.5	11.5
11	0.35	8.05
13	0.30	6.9
$15 \leq \nu \leq 39$ (odd harmonics only)	$3.85/\nu$	$88.55/\nu$

2.4.2 Harmonic Limits for Power Networks

IEC (International Electrotechnical Commission) :

IEC 61000-3-6 as discussed in [7] contains the harmonic restrictions for low voltage, medium voltage, high voltage systems. For the scope of this dissertation, the focus will be limited to low and medium voltage electrical systems and the standards in accordance to the IEC 61000-3-6 as found on table 2-6 below become relevant.

Table 2-6 IEC 61000-3-6 Harmonic voltage limits in LV and MV power systems, [7]

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order ν	Harmonic voltage (%)	Order ν	Harmonic voltage (%)	Order ν	Harmonic voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	> 21	0.2	10	0.5
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
$\nu > 25$	$0.2 + 1.3 \times (25/\nu)$				

Note: total harmonic distortion (THD) is 8%.

South Africa :

South African power quality standards w.r.t. voltage harmonics for both LV and MV power systems are enshrined in NRS048 [5] and IEEE519-1992 [8]. The NRS048 is largely an adoption of IEC61000-3-6 while IEEE519-1992 limits **THD to 5% and the individual harmonics to 3%**.

Section Conclusion : The harmonic standards provides customers with protection from effects of poor quality network voltage, with limits restricting individual harmonics and THD of the supply voltage. There are many network QOS standards applied around the world for managing harmonic levels for both the network and equipment (load). Typically the LV and MV power networks are managed through IEEE519 and IEC361000-3-6 standards while the end user loads (which in this case is lighting equipment) have their harmonic levels managed through international standards like the IEC 61000-3-2 or ANSI C82.

2.5 What are the Characteristics of CFL's ?

2.5.1 What are Energy Efficiency benefits of CFL's ? [18]

There are extensive papers and literature survey detailing the energy efficiency benefit of CFL's and it is used primarily for this purpose. This section will merely highlight an overview of energy efficiency including related topics like the impact to building heating and cooling and also the relationship to efficacy and embodied energy.

Energy Efficiency

The table 2-7 compares the power requirements of incandescent lighting to CFLs operating at various lighting (luminous) levels. The table arranges the lamps in order of ascending luminous output. CFLs are shown to efficiently use 20% - 33% of the power required for equivalent ILs. Given that residential lighting made up about 9% of the average US household's electricity consumption in 2001 which could be up to 7% of total American household consumption with the large scale deployment of CFLs.

Table 2-7 Electrical Power Equivalents for Differing Lamps, [18]

CFL (W)	IL(W)	Luminous (lumens)	Power Saved (W/h)	Power saved (%)
9–13	40	450	27-31	67.5-77.5
13–15	60	800	45-47	75.0-78.3
18–25	75	1,100	50-57	66.7-76.0
23–30	100	1,600	70-77	70.0-77.0
30–52	150	2,600	98-120	65.3-80.0

Efficacy and Efficiency

Efficiency for CFL technology ranges from 17 to 21% in the conversion of electric power to radiant power ranging from 60 to72 lm/W (lumens per watt) source efficacy against the 347 lm/W (100% theoretical max) luminous efficacy for radiation of tri-phosphor spectrum. As a result of the human eye light sensitivity will vary with the source lighting wavelength, the lamp output is then appropriately measured in lumens quantifying the effect from the lamps light spectrum to the eye. CFLs sources luminous efficacy are typically in the 60 to 72 lm/W range, while ILs are in the 8 to 17 lm/W range. Efficacy becomes relevant when wanting to meet the required illumination standards discussed in [42] to [45] in a very energy efficient manner.

Heating and Cooling

The replacing of ILs with CFLs inside a building results in a reduction of the building's indoor cooling requirement. For the periods when the building will require both lighting and heating, the additional heat required will be provided from additional demand on the heating system. In times when the building require lighting as well as cooling, then the CFLs deployed will reduce the cooling system's load resulting in additional savings in electrical power. This will provide an overall benefit to the energy bill in warmer climates.

Embodied energy

Although the energy required in the manufacturing CFLs are more than incandescent light bulbs, this embodied energy for CFLs are offset by the fact that they last up to 6 times longer and use up to 80% less energy (refer to table 2-7) than the equivalent ILs during it's lifespan.

Section Conclusion : CFLs were primarily designed as an energy efficient lighting technology yielding up to 80% energy savings when replacing ILs. Typical US households have an average of 9 % of their energy consumption made up from lighting which could drop to 7% if replaced with CFLs. In addition to this, efficiency from a consumption perspective is the relationship light output has to the power input i.e. efficacy (lm/W). The use of CFLs bring additional benefit to the constrained network by also reducing air cooling demand in warmer climates. It is the energy efficiency characteristics of CFLs when compared to IL that makes it attractive to both utility managing demand and customers managing their electricity bill.

2.5.2 What is the impact of CFL's on Power Factor ? [13], [15], [16], [17]

Using the [13], [15], [16] and [17] as a basis, the non-linear nature of CFLs are discussed further in this section. It is important to firstly understand displacement power factor that is expressed with the ratio of real power (i.e. units in Watts) to the apparent power (i.e. units in VA). The displacement power factor indicates the phase relationship of the current and voltage and for linear loads these waves will be in phase meaning that the power factor (PF) will be in unity approaching a theoretical maximum value of 1. In the case of non-linear loads both the current and the voltage waveforms will shift out of phase and the displacement power factor will reduce with a value measured by the displacement of these two respective waveforms. Similarly the difference in phase of the voltage and current could be minimised (i.e. an increase in the displacement power factor) by introducing either inductive or capacitive loading to the system.

$$\textbf{Displacement Power Factor} = \frac{\text{Real Power (W)}}{\text{Apparent Power (VA)}} = \cos(\text{power angle})$$

A distribution power network is most efficient if the voltage and current waveforms are closest to being in phase as this is when the current needed for a given quantity of real power will be optimal. As the PF decreases, the network losses increase as the system then becomes less efficient. The displacement power factor for almost purely resistive linear IL will approach values close to unity. Introducing of the older magnetic ballast non-linear CFL loads will also introduce a lagging power factor while the more modern CFLs provide leading PF. The older lagging PF CFLs may be beneficial as some urban power systems compensate with leading power factor as a result of the capacitance effects of underground cabling. However, typically a distribution network may have a lagging PF and the modern leading HPF CFLs may prove beneficial. To accommodate the either extremes of either leading or lagging power systems, the International Harmonizing Specifications prescribe variance of power factors to be between 0.5 and 0.9.

Distribution networks need to be designed to accommodate larger quantities of non-linear devices. Non-linear equipment cause harmonic currents, resulting in an increase of apparent power demanded and a power factor reduction. For a system containing both non-linear and linear devices, the power factor is best described by true power factor i.e. [W/(Vrms*Irms)]. The lower value for true power factor for CFLs reflect the non-linear equipment's harmonic currents conversion of useful power to wasteful harmonic reactive power.

$$\textbf{True Power Factor} = \frac{\text{Real Power (W)}}{(\text{Vrms})*(\text{Irms})} = \cos(\text{power angle})$$

In most instances the displacement power factor for the power system would be greater than the true power factor. To illustrate this example, one could consider that while the true power factor of a laptop may be 0.6, the displacement power factor may be as high as 0.9. The displacement power factor of incandescent lamps are as high as 1 because of the resistive nature. The non-linear nature of electronic ballasts in fluorescent lamps, typically have low power factors between 0.5 to 0.9 and recently also have high power factors that are higher than 0.9. HPF CFLs have additional components typically with at least a 25% premium on price, catering for reduction in both phase displacement and harmonics as well.

While true power factor calculations may apply to the power systems with non-linear loads, displacement power factor will be the more appropriate in determining the impact that harmonic loads have on a transmission network (especially in voltage constrained areas). In a typical household, CFLs are now outweighed by other non-linear household equipment like computers, refrigerators, and televisions with the displacement power factors from 0.5 to 0.9 would suggest that managing power factors may require a holistic approach. It should become mandatory that suppliers of electronic appliances should also be displaying the displacement power factor and the harmonic distortion on the product specifications nameplate and also ensure that all new product models match the best performance of it's market equivalent.

An important consideration would be to understand the impact of lifespan on electronic ballasts after many hours of usage. As a protective measure guarding against the possibility of power factor degradation due to ageing, one should rather utilise high displacement power factor and also introduce a requirement for the maintenance of CFL power factor based on lamp lifespan. To date there exists no conclusive documented evidence available to the public that clearly illustrate the effects of ageing on CFL electronic ballasts types.

South African standards like legislation in many places around the world also prescribe a displacement power factor of not less than 0.5 for CFLs. To date there has been no major system problems documented as a result of this CFL standard for many reasons that includes :

- The threshold for CFLs penetration level has not yet been reached to cause major issues;
- The issues that exist may not easily attribute to CFLs alone; and lastly,
- Many power systems have been designed to accommodate higher non-linear loads.

According to [14], correcting of true power factor excludes the traditional methods for correcting power factor. Typical PF analysis, use the ratio of active power to apparent power. Batch tests conducted with CFLs at 210V (i.e. rated voltage) highlights that CFL power factors range between 0.43 and 0.69 while the power factor range established from the testing of CFLs (with power ratings : 9W, 11W, 15W and 20W) at 220V (i.e. rated voltage) results in PF that ranges from 0.44 to 0.52.

Section Conclusion : Incandescent lamps being a purely resistive linear loads have displacement power factors at unity (pf = 1) while electronic ballasts in CFLs with their inherent non-linear nature were traditionally low power factor (LPF) but now may also include high power factor (HPF) as well. LPF CFLs have recommended power factors from 0.5 to 0.9 and power factors greater 0.9 recommended for HPF CFLs. HPF CFLs typically have additional components at a premium cost of about 25% of price [46], catering for reduction in both phase displacement and harmonics. Older and magnetic ballast CFLs have lagging power factors (inductive loads) while modern electronic ballast CFLs have leading power factors which may be beneficial to a distribution system with a lagging power factor.

2.5.3 What is the impact of CFL’s on Harmonics Distortion ? [14] - [16], [20] - [27]

According to [14] - [16], the non-linear nature of the CFL is characterised in this section. The introduction of nonlinear loads like CFLs particularly in large-scale installations may affect power quality of an already sensitive network. In harmonic sensitive networks, HPF CFLs compliant to IEC 61000.3.2 harmonic limits with low (less than 33%) THD with power factor (PF) in excess of 0.96 could be utilised to minimise the impact on power quality. As discussed in chapter 2.3, power quality broadly refers to reliability of supply and voltage quality. For the purposes of this dissertation, our interest would be the extent that voltage quality is put at risk by harmonics of CFLs in large scale implementation. Harmonics are becoming a concern in recent times as non-linear loads including CFLs on the system grow.

Large scale CFL programmes could increase the harmonic levels on the power network which could result in a more resistive loss and voltage stress which are often difficult to identify and could remain undetected for a while. Some practical indications of high harmonic levels may manifest in the forms of symptoms as follows :

- Transformer overheating, results in early failure and reduced lifespan up to 50% by operating 10ºC above its rated class.
- Motor overheating due to increased voltage distortion resulting in a decrease in efficiency particularly the 7th harmonic which can cause torques which can stall motors.
- Control systems malfunction.
- Conductor overheating due to high harmonic current in the neutral conductor especially the triplen harmonics found to be additive in a 3 phase system.
- Overloading of capacitors as a result of higher harmonic frequency current flows leading to premature ageing.
- Interference with electronic equipment like telecommunication systems and computers. Harmonics result in interference with the radio and phone systems especially where harmonics are at frequencies in vicinity of the carrier signal in pilot wire carrier system.
- Nuisance circuit breaker tripping and fuse malfunction as a result of overheating protection. The distorted sine-waves results in overcurrent devices correctly tripping despite the loading calculation assumed a pure sine-wave mains voltage, that typically appears to be within the equipment rating. Depending upon the network characteristics, problems may be exacerbated.
- Disturbances in ripple control systems.

In South Africa like in many countries, all electronic equipment need to adhere to the harmonic limit standards as prescribed by IEC 61000.3:2. It is important to note that harmonics will be produced by many other appliance at home including TV's and personal computers. Tests like conducted in chapter 3 highlight the correlation between LPF CFLs with higher harmonic currents while the harmonic performance of HPF CFLs are more compliant to IEC 61000.3.2. Industrial and commercial customers are expected to take appropriate measures to manage harmonic levels. These on site measures include installing of harmonic filtration equipment while addressing power quality issues caused by widespread deployment of CFLs throughout the residential networks are not easily identified and may require more expensive network harmonic filtering equipment.

LPF CFLs presents loads with unfavourable harmonic current spectrum i.e. with huge THD values. It is for this reason that many technical papers focus on the investigation into the CFLs current harmonic spectrum content under varied supply conditions. Tests showed that the THD for current, determined as a ratio of the fundamental current(I1) is clearly expressed with the formula below ranged from 82.4 to 109%.

$$\mathrm{THD_I} = \frac{\sqrt{\sum_{v=2}^{v=\infty} I_v^2}}{I_1}$$

Table 2-8 THD(%) of different lamps at different supply voltages [21]

Lamp power	Voltage				
	190 V	200 V	210 V	220 V	230 V
9 W	117.2	118.3	120.4	121.7	122.4
11 W	102.4	104.6	107.9	108.9	110.9
15 W	128.2	133.1	133.9	134.5	137.4

In [20] and [21], clearly highlights the results of voltage variations on CFL performance. The relationship between CFL rms voltage and the current THD as found in table 2-8 above. It was observed that the THD of CFL current increased with increase in the supply voltage. The diversity factor effect(partial harmonic cancellation) was observed when various CFLs operating in parallel where the THD is measured to be lower as compared individual lamps. In [22], it is highlighted how a bigger mix of lamp types ie. LED with CFLs could result in the THD impact being reduced. An overall diversity factor for a customers that are separated by cables will give rise to further reduction in THD.

In discussions found in [23] and [24], it is noted that CFLs connected to distorted supply voltage having varied THD factors have fixed ratios for the individual harmonics. These ratios for individual harmonics and the THD were found to be 4.6% (lower end value), 15.5% (midrange value) and 36.4% (higher end value). In addition to current distortion shown to be affected by the supply, it was also shown to be affected by individual harmonic ratios. It is highlighted that current THD changes are not directly proportional to the changes in the voltage THD. The rise of the voltage THD from a medium to high distortion level results in significant change in the current THD. The investigation findings documented in [25] revealed that the THD for current is minimum when the supply voltage THD was 10% with non-linear correlation between the same order harmonics for supply voltage to the CFL current as expected because of the CFLs non-linear electrical circuit.

In [27], the paper highlights the complexities in the modelling of CFLs when deployed in real life applications and conditions, which has been characterized with the supply voltage variable rms value and also variable voltage wave. The models were mostly limiting as the analysis of the voltage THD for typical LV installations, were mostly based on the current harmonic range of CFLs utilised assumed to be according to the prescribed standard maximum limits. It is however noted that the test results revealed the current harmonic in some cases actually exceeded the prescribed limits.

Section Conclusion : It is highlighted that CFLs are non-linear loads and generate current harmonics that are that not within the harmonic limitations prescribed in IEC 61000-3-2. There exist a noticeable relationship between LPF CFLs and high harmonic currents. It should also be noted from papers discussed that performance of harmonics for the commercially available HPF CFLs priced with about a 25% premium [46] are improved and are compliant to IEC 61000-3-2 when compared to LPF CFLs. The THD for lamp current drawn increase with increases in mains supply voltage. The relationship between CFL rms voltage and current THD are shown in table 2-8 above. There is no proportional relationship shown to exist between the current THD and the voltage THD. An increase of voltage THD from a medium level to a higher level of distortion results in a variance in the current THD. As expected from CFLs being non-linear devices, no direct correlation found between the mains supply voltage harmonics of the same order and the lamps current. Modelling of CFLs performance is complex especially for real working conditions.

2.5.4 Global Comparison of the CFL Specifications and Standards ? [28] - [30], [33]

This section highlights the general lighting industry specifications for CFL's but at the same time compare the Australian approach to the South African approach and also highlight the silence w.r.t. harmonics. The widespread CFL deployment makes consumers concerns relevant w.r.t. the accuracy of manufacturers claims relating to the lamp's efficiency, performance and lifespan. The Minimum Energy Performance Standard(MEPS) for CFLs was an Australian response like many jurisdictions to this relevant public concern. In some instances MEPS is effective in also imposing mandatory power quality standard requiring compliance. [28]

Manufacturers differ with significant variances in the cost, turn-on time, light quality (including CFLs that may appear identical with the same color temperature) hence CFL specifications and standards are essential to maintain a minimum acceptable quality. Typically CFL specifications and standards covers the following areas :-

Starting time : Unlike incandescent lighting's turn in a fraction of a second, CFLs take within a second to turn on.

Design and application issues : High electrical efficiency and durability.

Size : This relates to the practicality w.r.t. the fit into existing IL fixtures.

End of life : CFLs may also fail as a result of the electronic ballast having many component parts over and above failure from normal wear.

Dimming : Only some CFLs are labelled for dimming control.

Perceived coldness of low intensity CFL : Unlike ILs, CFLs colour temperature is constant when dimmed, explaining it's popularity in bedrooms where a subdued lighting is preferred.

Infrared signals : CFLs also emit an infrared light that could be interpreted as a remote signal by the electronic devices operated by infrared remote control.

Heat : consideration for impact of heat shortening the lifespan of certain ballast should be labelled and operated for base down operation.

Time to achieve full brightness : typically CFLs provide under 80% of its rated lighting output when switch on before warm up which could take up to 3 minutes.

Audible noise : Older model CFLs like fluorescent lighting may emit a buzzing sound.

Use with electronic controls : CFLs electronic ballast may experience shortened lifespan as result of interference from electronic timers.

Iridescence : At night florescent lamps can exhibit iridescence on window film.

Outdoor use : CFLs may not start in cold outdoor weather as they are designed for indoors.

Lifetime brightness : Fluorescent lamps luminosity gets dimmer with time and may be inadequate after 40% of lifespan.

While these CFL specifications are important considerations for quality of lighting, very little is covered relating to managing their impact to the power network w.r.t. power factor and nothing is covered w.r.t harmonics.

- **Power Factor :** In Australia although MEPS were only covering linear fluorescent tube lamps, the plan was to include CFLs under the 'Green Light Australia' programme. The minimum mandatory standard proposed by MEPS for CFLs recommends 0.5 power factor for LPF CFLs and a voluntary 'high efficiency' standard of 0.9 power factor for HPF CFLs. It is important to note that a minimum power factor requirement also contains an implicit requirement for harmonics whereby the electronically ballasted CFL HPF technology can only achieve the power factor of 0.9 with a built-in harmonic filter. It is highlighted in the GreenLight strategy that the standard for HPF CFLs could be introduced by phasing out LPF CFLs. [28]

- **Harmonics :** Despite the omission of harmonic standards in CFL manufacturers specifications, harmonics can have a significant contribution to power quality, especially in instances of large-scale CFL programmes. In these situations, CFLs with THD under 33% and PF above 0.96 are to be used to minimise impact. EU standards like IEC 61000-3-2 prescribes harmonic limitations for equipment drawing phase current less than 16A. IEC 61000-3-12 accommodates equipment consuming under 75 A per phase but greater than 16 A. IEC 61000-4-7 governs the measurement and evaluation methods for harmonics.

The IEC committee members evaluated classifications that groups equipment into one of 4 classes based on the following criteria :

- Harmonics spectrum, including phase for current drawn by the equipment,
- Co-incidence of the same type of equipment used simultaneously,
- Quantity of equipment used by consumers
- Duration of use of equipment,
- Equipment power consumption.

Table 2-9 below highlights the equipment classification according to IEC 61000-3-2 after consider the above mentioned criteria :

Table 2-9 Harmonic standard IEC 61000-3-2, equipment classification, [29]

Class A	• "Balanced three-phase equipment • Tools excluding portable tools • Household appliances, excluding equipment identified by Class D • Audio equipment • Dimmers for incandescent lamps • Everything else that is not classified as B, C or D
Class B	• Arc welding equipment which is not professional equipment • Portable tools
Class C	• Lighting equipment
Class D	• Television receivers • Personal computers and personal computer monitors **Note:** Equipment must have power level 75W up to and not exceeding 600W"

2.5.4.1 Australian Minimum Energy Performance Standards (MEPS), [30]

The South African Government need to consider introducing policy like the Australian Government's that attempts to adopt practices that are world best, wherever practical. CFLs that are self-ballasted are to comply with the most severe MEPS and endorsed energy performance labels used in China, while other criteria comply with to other programs with harsher levels of standards.

CFLs as a 'prescribed' product in Australia, will have to meet the relevant safety standards. Australian Green Office (AGO) initiated a voluntary program for lamp labelling. These become important considerations since consumers are concerned about lamp issues including the lamp lifetime, colour and start-up time. The major performance criteria like efficiency level, start-up time, lumen maintenance, power factor, lifetime (rated average), colour rendering, CFL lifetime claims, mercury content, equivalent IL, are to be included and considered in the Australian program.

There would be 2 sets of standards i.e. one set for performance levels with MEPs and the other more stringent set for the lamps endorsement label. [30]

2.5.4.2. South Africa's Compulsory Performance Requirements for CFLs, [33]

According to [33], South Africa's January 2008 national load shedding has created the need for quality CFLs. In support of country's energy saving drive, required that these lamps comply to both standards for safety and minimum performance. In many instances CFLs light output and lifespan did not meet manufacturers claims and often consumers experience issues with the starting of the lamps. To protect the consumer which will support the country's effort to save energy, a compulsory specification was proposed with minimum requirements for CFL efficiency, lumen maintenance, power factor, starting, EMI and life.

Fig 2-4 CFL in the Cap Position, [33]

Standards South Africa (STANSA) has proposed to amend the South African standard SANS 60901/IEC 60901 performance specifications for single capped fluorescent lamps (as shown in fig 2-4) to also include the national requirement for energy efficiency. The international standard IEC 60901 has been modified to include energy efficiency requirements suitable for South African conditions i.e. SA standard voltage and also specify values for starting, luminous efficacy and life.

The Regulatory Department of the SABS was to compile a standard that refers to the South African performance requirements as found in Annex AA in SANS 60901 and the standard on the safety of CFLs SANS 61199 that was to be declared compulsory by the Minister of Trade and Industry. National requirements for energy efficiency as in draft National Amendment 1 to SANS 60901/IEC 60901 performance specifications for single capped fluorescent lamps are discussed below. [33]

The CFL requirements on energy efficiency included in the amendment most suitable to meet national compulsory requirements summarised as follows :

- **Starting :** At the test voltage, the lamp shall start within 1,5 s as starting of the lamps especially during winter or rainy weather is usually problematic.
- **Luminous flux :** The lamp efficiency calculated from the initial luminous flux and initial power measurements. In SANS 60901/IEC 60901 it is stated that the initial power reading shall be limited to the rated power by more than 5% (+ 0,5 W).

Since lamp efficiency became critical in the energy saving drive, requirements for minimum lamp efficacy, expressed as lumen per watt (lm/W) as general the light output (W) of many CFLs don’t match their claims. Some results obtained in the laboratory are given in Table 2-10 below. This has relevance when trying to meet illumination requirements [42] – [45] in an efficient manner.

Table 2-10 Lamp Efficacy, [33]

Lamp Power Rating (W)	Lamp Efficacy lm/W, Min
< 15	45
> 15	55
< 14 with translucent cover	40
15 – 19 with translucent cover	48
> 20 with translucent cover	50

In cases where the CFL light output does not compare to the replaced IL then the incentive to replace an incandescent lamp with a CFL is lost considering a significant price differential. [33]

- **Power factor :** The power factor (as per vector representation in figure 2-5) of a lamp shall not be less than 0,5. Leading power factors ranging between 0,52 and 0,56 were measured on known trade name self-ballasted CFLs. In cases where consumer reticulation is designed for lagging power factor may experience this change from a resistive circuit to a capacitive circuit causing switching problems from large inrush currents and switching oscillations. [33]

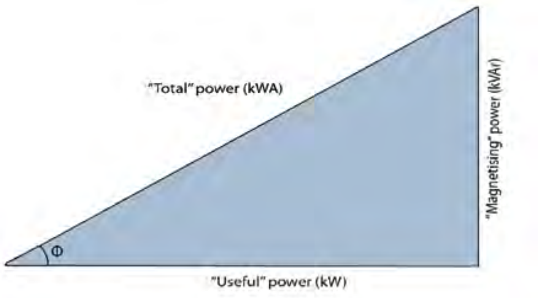


Figure 2-5 Power Factor Correction Vector Diagram, [33]

- **Electromagnetic Interference Suppression :** The lamp shall comply with CISPR 15 (SANS 215). CISPR 15 is the international standard specifying limitations and methods of measuring characteristics of CFL radio disturbance and also for similar lighting equipment.

- **Lumen Maintenance :** After 2000 h operation, the luminous flux of most lamps shall be at least 80% of the initial value as it deteriorates rapidly during this period before stabilising to a slow deterioration pace. Although the initial luminous flux could be acceptable, the result of deterioration results in the lamp operating for the most part of its life at low efficiency than claimed.

- **Lamp Life :** Each lamp shall have a life of at least 2000 h, and after 6000 h operation at least 50% of the lamps in the sample shall remain burning as shown in figure 2-6 below. This is an important consideration when lamps need to sustain prescribed health and safety standards illumination limits for lifespan of lamp.

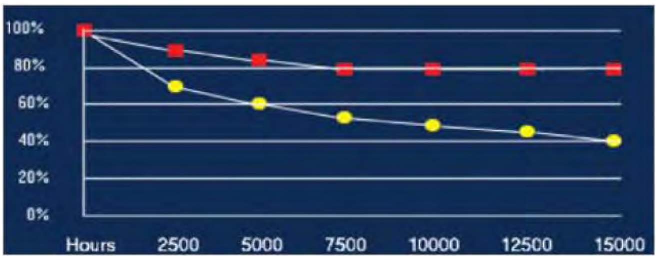


Figure 2-6 : Lumen depreciation versus burning hours, [33]

Theoretically an incandescent lamp's rated life is 1000 hour which gives CFLs a factor of 6 times longer life although experience in many cases has proved differently. CFLs with short lifespans do not support the energy saving drive. South Africa needs CFLs complying with not only compulsory safety standards, but also with compulsory performance standards in support of the energy saving drive. However, it is important that the compulsory requirements be regulated and that the quality of the CFLs sold in our country be monitored for compliance with the compulsory standard. [33]

2.5.4.3 Other South African National CFL Standards

In addition to the above, listed below are also other South African standards applicable to CFL :

- SANS 215 (SABS CISPR 15:2007) : Limitations and methods of measuring characteristics for electrical lighting radio disturbance and also for similar equipment,
- SANS 61000-3-2 (SABS IEC 61000-3-2:2006) : Electromagnetic compatibility (EMC) Part 3-2: Limits – Limitations for harmonic current emissions,
- SANS 61000-3-3 (SABS IEC 61000-3-3:2006) : Electromagnetic compatibility (EMC) Part 3-3: Limits - Limitations for changes in voltage, fluctuation in voltage and flicker in public LV power systems for equipment rated for ≤ 16 A per phase and not subject to conditional connection.

Section Conclusion : It can be seen that the standards in place focuses on many important aspects of efficient lighting performance such as efficacy, efficiency, CFL labelling, safety, lifespan and PF but nothing pertaining to the limits for harmonics as prescribed in the IEC 61000-3-2. Power Factor that is applied in the South African standards recommends limits for the lower power factor (LPF) CFLs which has an implicit correlation to accommodate higher levels of harmonics. It is interesting to note that New Zealand unlike South Africa have already adopted the more stringent Minimum Energy Performance Standard (MEPS) CFLs, which immediately requires a 0.9 power factor and harmonic limits as prescribed in AS/NZS61000-3-2, giving important consideration to the QOS impact for lighting equipment. The Australian Green Light strategy recommends a phasing out strategy for the LPF CFLs to accommodate the HPF CFL standard to be phased in. Given the importance of managing harmonic limits to ensure a good quality of supply, it is important that the lighting industry and utilities embarking on large scale efficient lighting programmes adopt IEC61000-3-2 for harmonics and PF limits for lamps procured. Further reading, [42] to [45], found at the end of the reference section on required illumination level which is also an important consideration when applying lighting in specific areas governed by health and safety regulation pertaining to minimum illumination level that need to be maintained throughout the lifespan of the lamp.

CHAPTER 3 : LABORATORY INVESTIGATIONS

3.1 Introduction :

One of the simplest ways to conserve energy in the residential market is through efficient lighting technologies like the compact fluorescent lamp (CFL) which easily replaces the conventional incandescent lamp (IL). The electronic ballasts makes CFLs nonlinear equipment, drawing a distorted current sine-wave because of harmonics. The harmonic current that flows into the network introduce problems with quality of power. These current harmonic emissions flowing through the system could cause :-

- distortion to the mains supply voltage waveform,
- damage to power factor correction capacitors as they are also sharing the network and have lower impedance at higher frequency harmonics,
- equipment malfunction eg. crawling of motors,
- interference with telephones,
- adverse/erratic behaviour or even complete malfunction of some equipment such as PLCs, due to voltage distortion,
- costly reduction in equipment lifespan which is not easily or immediately apparent.

Previously the harmonics injected into the network by these lamps have been disregarded with no consultation with the network engineers responsible for QOS especially on problematic networks. It is more practical to manage the problem before rather than after. The simplest manner to achieve this is by ensuring that the CFLs installed comply with international standards like IEC61000-3-2 w.r.t harmonic levels and PF. This additional cost differential for QOS from large scale CFL rollouts can be contributed by the respective QOS department fitting this bill pro-actively upfront rather than reactively and sporadically trying to manage complaining customers from problematic networks.

3.2 Intended Purpose of the Experiments :

To be able to assess the impact of CFLs on power networks it is important to firstly understand the non-linear nature of this equipment load and its power factor. This investigation will quantify all technical performance w.r.t. rated or unrated specifications although it specifically seeks to evaluate and confirm characteristics of the CFLs especially concerning harmonics and power factor under normal input supply conditions. The results of the laboratory tests for the

CFLs of different brands and quality were assessed for compliance to IEC 61000-3-2 harmonic current limits. Refer to table 3-1, table 3-2 and figure 3-1 below for the IEC current harmonic limits for efficient lighting like CFLs.

Table 3-1 International Harmonic and PF limits

	THD Limit	3rd Harmonic	5th Harmonic	Higher Order Harmonics Limit	PF Limits	Size / Equip. Limit	Comments
ANSI (C28)	32.0%	7.0%	7.0%	7.0%		Elect. Balla	Many American utilities apply THD limit of 20% in EE programs
AS/NZ 61000.3.2:2003		86.0%	61.0%			<16A(25W)	This superceded the AS3134 standard (for class D equipment)
IEC	33.0%				0.96	< 25W	

Table 3-2 Harmonic and PF limits as per IEC 61000-3-2

Harmonic Order v	Harmonic Current Max. Limit (A)	Harmonic Current per Watt Max. Limit (mA/W)	Harmonic Current as % of Fundamental (%)
3	2.30	3.40	78.20%
5	1.14	1.90	43.70%
7	0.77	1.00	23.00%
9	0.40	0.50	11.50%
11	0.33	0.35	8.05%
13		0.30	6.90%
15≤v≤39 (odd harmonics)		3.85/v	88.55/v

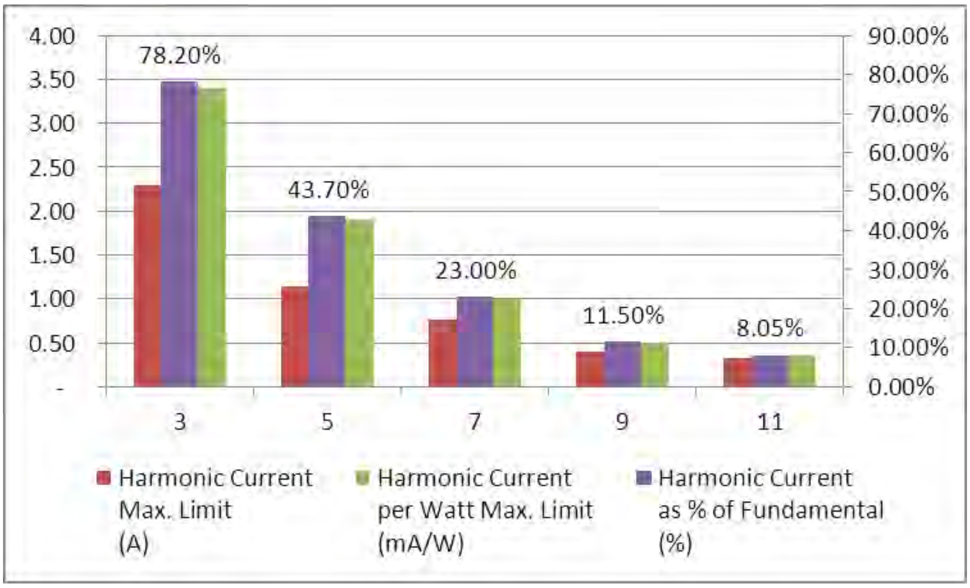


Figure 3-1 Lower Frequency Harmonic Limits as per IEC 61000-3-2

3.3 Methodology for Laboratory Tests

3.3.1 Preparing of Test Rig : A domestic lighting test rig was constructed from wood, electrical fittings and switches in Eskom's Plant Department's laboratory in East London. The test board (as shown on figure 3-2 and figure 3-3) was configured to be supplied through the mains supply and a voltage regulator. The test board was also configured for power quality measurements to be taken easily from an Impedograph power quality recorder. My laptop was loaded the appropriate CT Lab software to download data directly from the Impedograph.

Figure 3-2 Test Equipment

Figure 3-3 Test Equipment

Figure 3-4 Lamps Tested

The test equipment was set up for the first batch test to investigate the CFLs characteristics and technical performance as per schematic in figure 3-5 below.

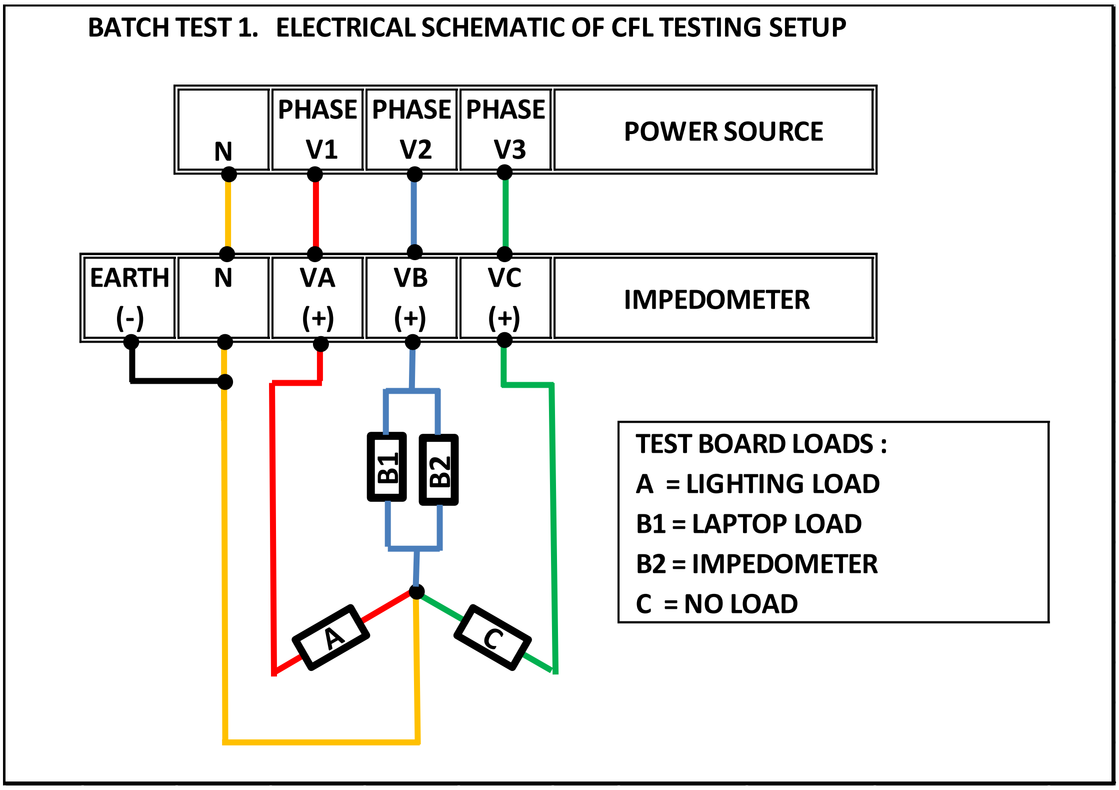


Figure 3-5 Batch Test 1 Electrical Schematic of the test equipment set-up

The test equipment was then set up for the second batch test to investigate the CFLs technical performance when interacting with other load types as per schematic in figure 3-6 below.

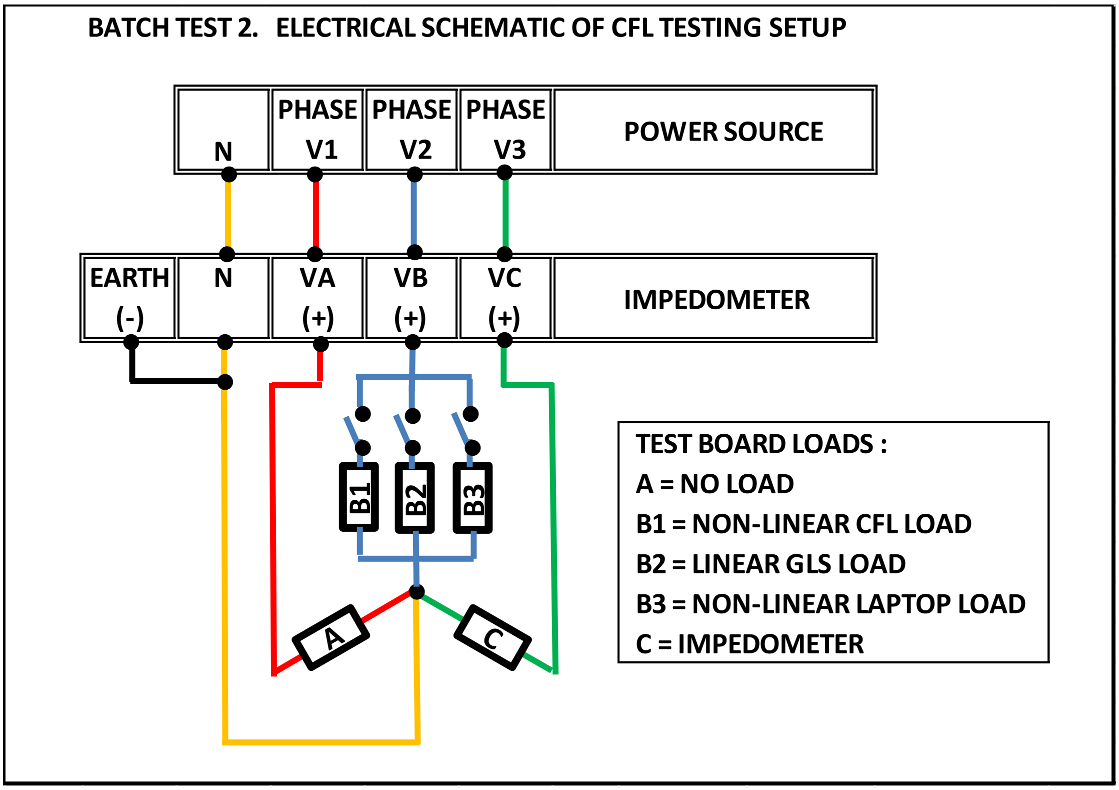


Figure 3-6 Batch Test 2 Electrical Schematic of the test equipment set-up

3.3.2 Choice of Lamps : The lamps (as shown on figure 3-4) where sourced from Eskom, local supermarket and a reputable lighting supplier to ensure that there is a fair spread of lamps. The choice of lamps as in Table 3-3 was a to ensure a variety of i.t.o. the following :-

- Manufactures,
- Load factor type i.e. high load factor vs low load factor,
- Wattage range i.e. 9W to 45W,
- Environmental compliance for mecury content i.e.ROSH vs non-ROSH lamps,
- Lamp standard compliance,
- Light type i.e. cool white vs warm white,
- Manufacturing quality standards,
- Samples from recent Eskom large scale CFL programmes eg. LeeLite and Eskom Not For Sale,
- An incandescent light (IL also referred to as GLS).

Table 3-3 Range of Lamps Tested

No.	Lamp Brand	Tube Type	Rated V	Rated W	Lumens	Colour	Rated Life	Cap Type	Energy Label	Lamp Std	Quality Std	Enviroment Std
1	Radiant	4U	240V	45W	2500Lm	CW 4000K	8000 hrs	E27	B			
2	Eurolux	3U	240V	20W	1100Lm	CW	6000 hrs	E27	B			
3	LeeLite	Tornado	230V	15W	845Lm	WW 2700K	10 years	B22	A	SANS 60969	ISO 9001:2000	ROHS
4	Megaman	3U	240 V	15 W	800Lm	WW 3000K	15000 hrs	E27	A	IEC 60969	ISO 9001:2000 SA8000 OSH18001 ISO 14001	
5	Megaman	2U	240 V	9 W	405Lm	WW 3000K	15000 hrs	E27	A	IEC 60969	ISO 9001:2000 SA8000 OSH18001 ISO 14001	
6	Philips Genie	3 U	240 V	14 W								
7	Eskom NFS	3 U	240 V	14 W								
8	Pila	2U	240V	15 W								
9	Mr Electric	3 U	240 V	15 W		CW 4000K	6000 hrs	B22				
10	Philips	GLS	240 V	60 W								

3.3.3 Preparing of Lamps for Test : Only brand new CFLs were tested. Before applying the test procedure, individual CFLs were operated with an input voltage from mains supply for a 60 minute period for stabilised conditions. These tested CFLs were mounted base down on the custom built test board as shown on figure 3-3 above. All tests were performed at the Eskom's Plant department's laboratory in East London where the room temperature is not well regulated.

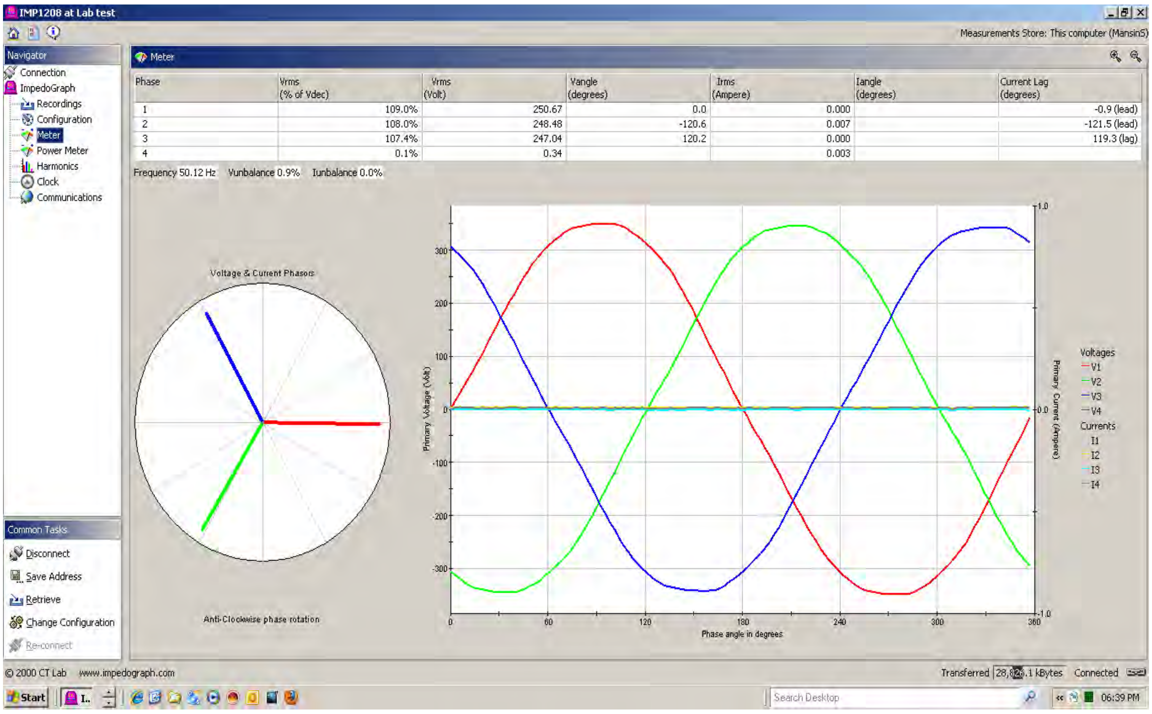
3.3.4 Test Procedure for Lamps :-

- At the start of each of the test periods, each individual CFL was stabilised at mains voltage (250V) for a 60 minute period.
- The stabilised CFL at mains voltage, was then observed for 5 minutes thereby allowing for the stabilised CFL load to be recorded.
- The Impedograph was utilised to conduct all power quality measurements. This recorder monitors voltage quality according IEC61000-4-30 (Class A), NRS048 (2003), EN50160, IEC61000-3-6/7 standards.
- The Impedograph was configured to record over a 60 seconds period, the fundamental and individual harmonics for both the current drawn and voltage supplied up to the 25th order and also the standard power measurements (i.e. the real power, the active power, the apparent power and the true power factor) for the 60 seconds duration.
- The Impedograph was wired to 3 phase mains supply in Star connection (4 wire).
- A voltage regulator was not operational at the time of testing to conduct further tests at 207V and 230V.
- The test rig was connected to the 1st phase (V1, I1) of supply while the impedograph and the laptop were connected to the 2nd phase (V2, I2) of the supply and the 3rd phase had no load.

3.4 Batch Test 1 : Laboratory Tests for CFL characteristics

3.4.1 Laboratory Test Results : Main Supply

The power quality of the mains supply was first analysed to establish the basis for the tests. The Impedograph was used to observe waveforms for both the current and voltage in addition to the inherent harmonic content of the mains supply. From the results below it is clear that the 3 phase supply of the Eskom building at East London is supplied at 250V.



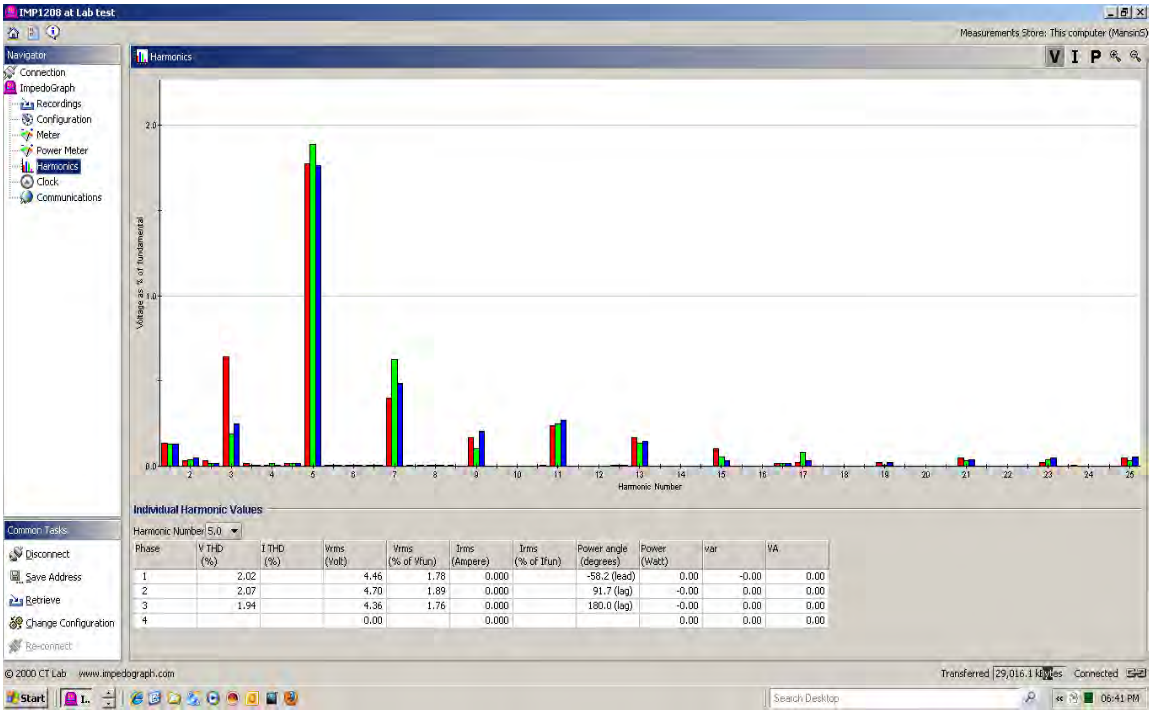
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	109.0%	250.67	0.0	0.000		-0.9 (lead)
2	108.0%	248.48	-120.6	0.007		-121.5 (lead)
3	107.4%	247.04	120.2	0.000		119.3 (lag)
4	0.1%	0.34		0.003		

Frequency 50.12 Hz Vunbalance 0.9% Iunbalance 0.0%

Figure 3-7 Voltage and Current Waveforms for Mains Supply

From the results in figure 3-7 above it should be noted that the 3 phase supply to the Eskom building at East London (Sunilaws Office Park) is supplying the building with 250V. Hence these tests conducted on lamps will be at 250V and not the nominal supply voltage of 230V. It is not an issue as this is within the voltage prescribed in the NRS048 which is 230 V ± 10% i.e. still within the upper voltage limited of 253V.

It is for this reason that further tests are recommended at a later stage to ensure that we observe performance of these lamps under nominal voltage of 230 V and the lower voltage limit of 207V. This could be achieved by applying a voltage regulator to the input voltage to the lighting test rig to ensure that the performance of these devices can be observed at the voltage range as prescribed by NRS048 i.e. 230V ± 10%.



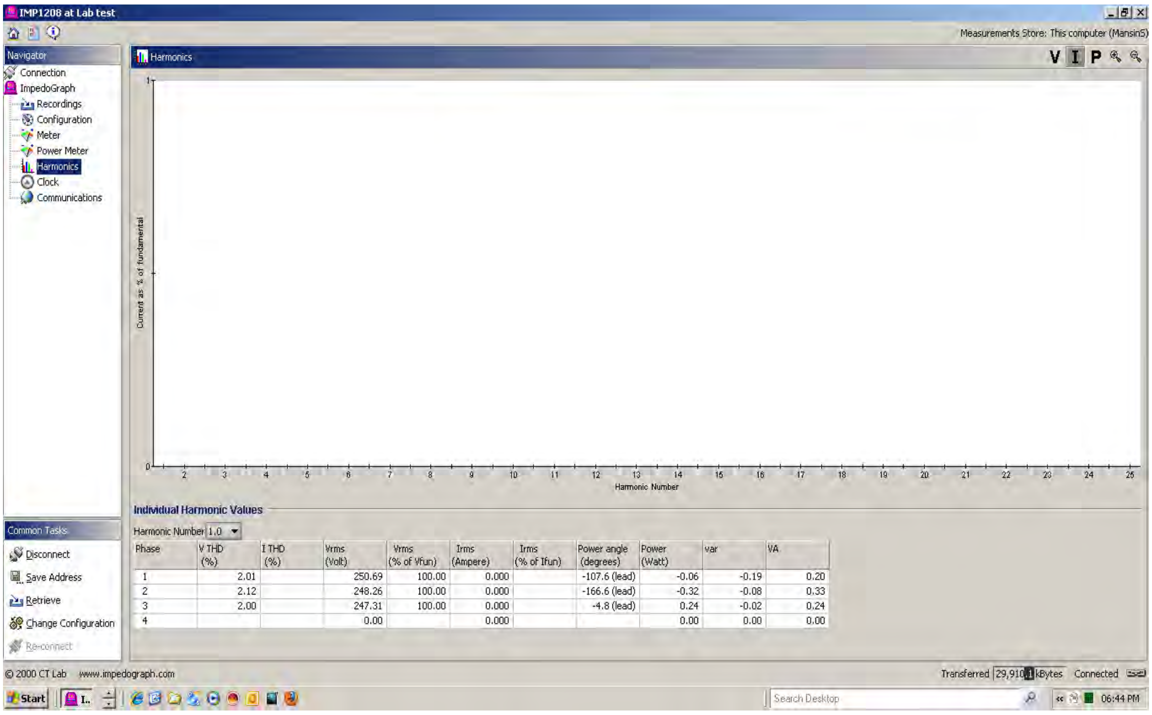
Individual Harmonic Values

Harmonic Number 5.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.02		4.46	1.78	0.000		-58.2 (lead)	0.00	-0.00	0.00
2	2.07		4.70	1.89	0.000		91.7 (lag)	-0.00	0.00	0.00
3	1.94		4.36	1.76	0.000		180.0 (lag)	-0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-8 Voltage Harmonics for Mains Supply

The figure above shows that the supply has a very noticeable 5th voltage harmonic around 1.8% of the fundamental that is followed by a 7th and 3rd harmonic at around 0.5% of the fundamental.



Individual Harmonic Values

Harmonic Number 1.0

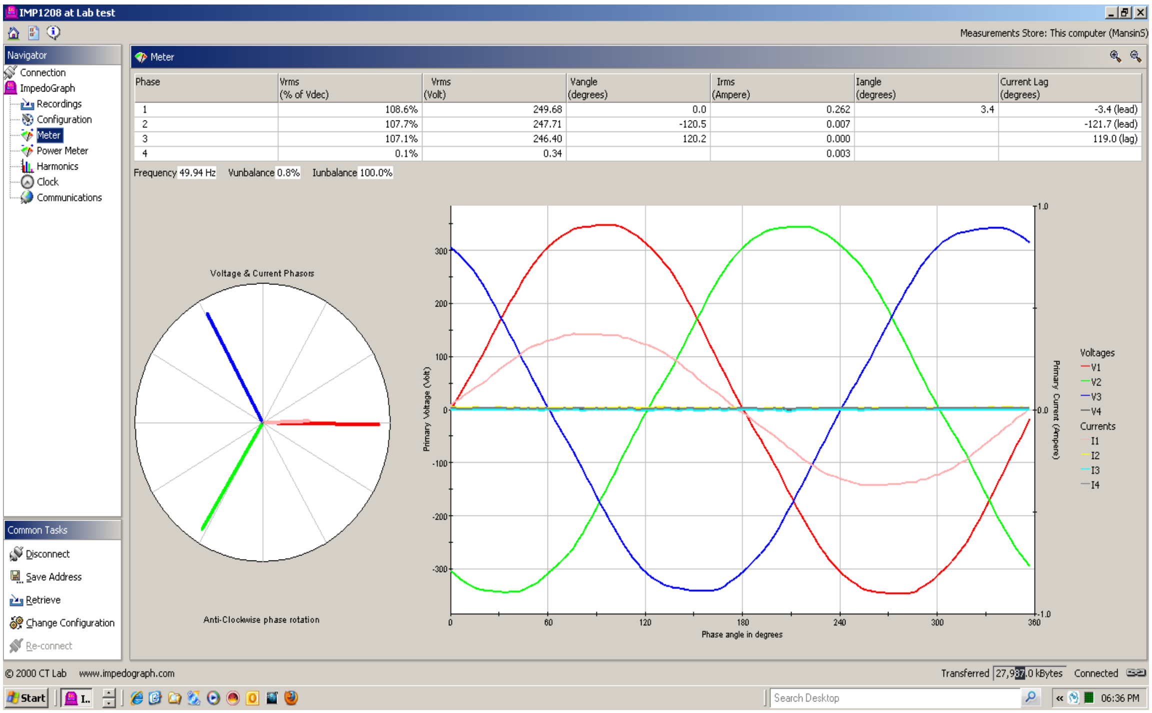
Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.01		250.69	100.00	0.000		-107.6 (lead)	-0.06	-0.19	0.20
2	2.12		248.26	100.00	0.000		-166.6 (lead)	-0.32	-0.08	0.33
3	2.00		247.31	100.00	0.000		-4.8 (lead)	0.24	-0.02	0.24
4			0.00		0.000			0.00	0.00	0.00

Figure 3-9 Current Harmonics for Mains Supply

No load connected to the mains hence no current harmonics observed in the figure 3-9 above.

3.4.2 Laboratory Test Results : Incandescent Light Bulb (Philips, 60W)

It is important to understand the performance of an incandescent light bulb (IL) as the original lighting load that is to be displaced with an energy efficient CFL. The power quality of the IL load was first observed with the Impedograph before the efficient compact fluorescent lamps. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



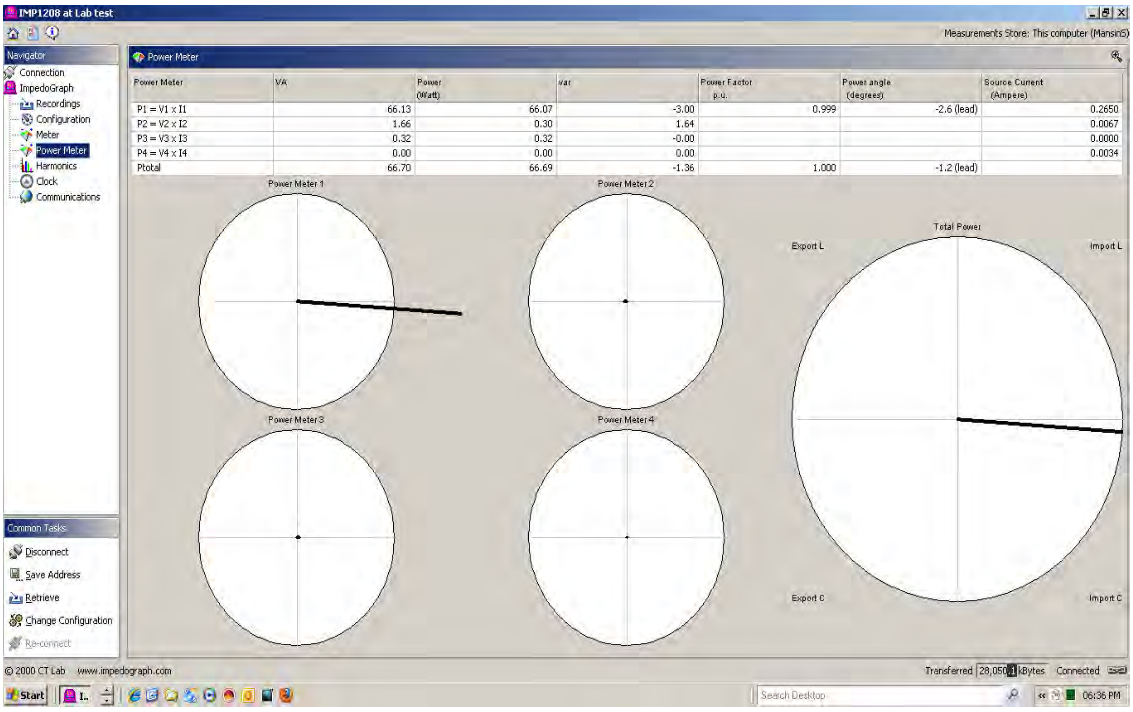
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.6%	249.68	0.0	0.262	3.4	-3.4 (lead)
2	107.7%	247.71	-120.5	0.007		-121.7 (lead)
3	107.1%	246.40	120.2	0.000		119.0 (lag)
4	0.1%	0.34		0.003		

Frequency 49.94 Hz Vunbalance 0.8% Iunbalance 100.0%

Figure 3-10 Voltage and Current Waveforms for Incandescent Light Bulb

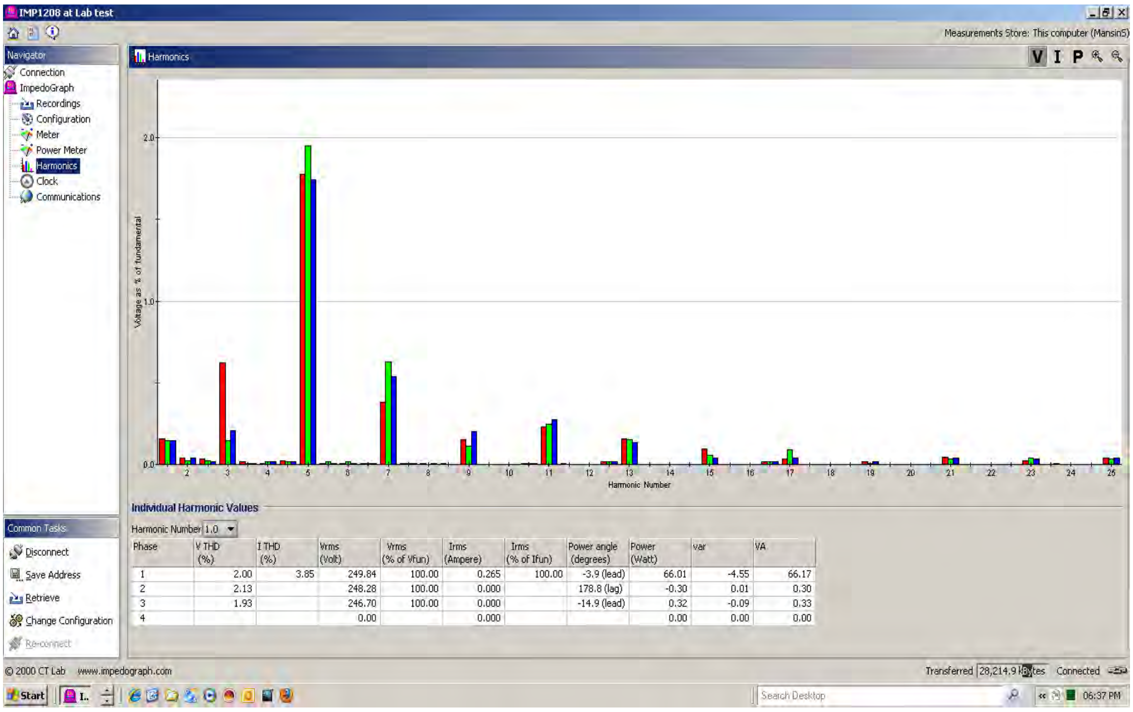
As expected I1 is noted to be in phase with V1 and the wave forms appears to be sinusoidal as expected being a linear resistive load. There is minimum load connected to the 2nd and no load to the 3rd phase of the mains supply hence no current flow observed.

As observed in Figure 3-11, the power factor is not exactly unity at 1 but 0.999 as there is a possible almost negligible noise in the form of capacitive load noted.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	66.13	66.07	-3.00	0.999	-2.6 (lead)	0.2650
P2 = V2 x I2	1.66	0.30	1.64			0.0067
P3 = V3 x I3	0.32	0.32	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	66.70	66.69	-1.36	1.000	-1.2 (lead)	

Figure 3-11 Power Meter Readings for Incandescent Light Bulb



Individual Harmonic Values

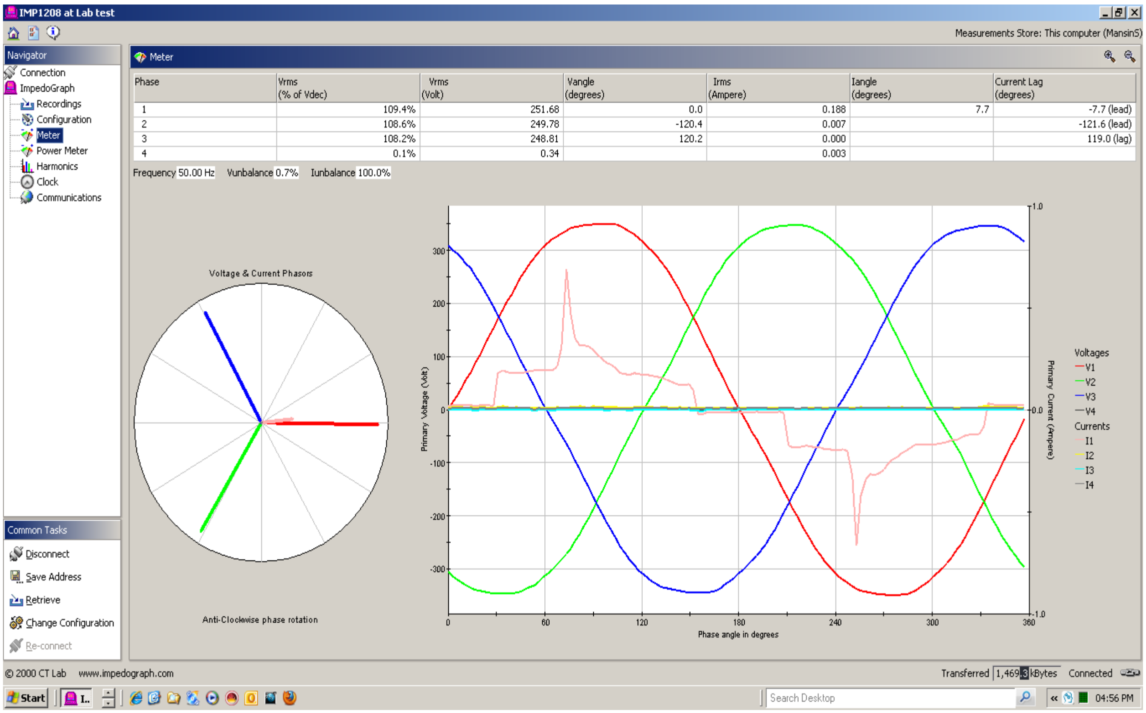
Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.00	3.85	249.84	100.00	0.265	100.00	-3.9 (lead)	66.01	-4.55	66.17
2	2.13		248.28	100.00	0.000		178.8 (lag)	-0.30	0.01	0.30
3	1.93		246.70	100.00	0.000		-14.9 (lead)	0.32	-0.09	0.33
4			0.00		0.000			0.00	0.00	0.00

Figure 3-12 Voltage Harmonics for Incandescent Light Bulb

As per figure 3-12 above, the voltage harmonic spectrum observed is very similar to the supply without loading i.e. it has a very noticeable 5th harmonic around 1.8% of the fundamental that is followed by a 7th and 3rd harmonic at around 0.5% of the fundamental.

3.4.3 Laboratory Test Results : HPF Compact Flourescent Lamp (Radiant, 45W)

This is the only high power factor (HPF) CFL that was managed to be sourced for these laboratory tests although of a higher wattage. It is important to have an understanding of the characteristics of a HPF CFL to be able to draw a comparison to a low power factor (LPF) CFL. The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



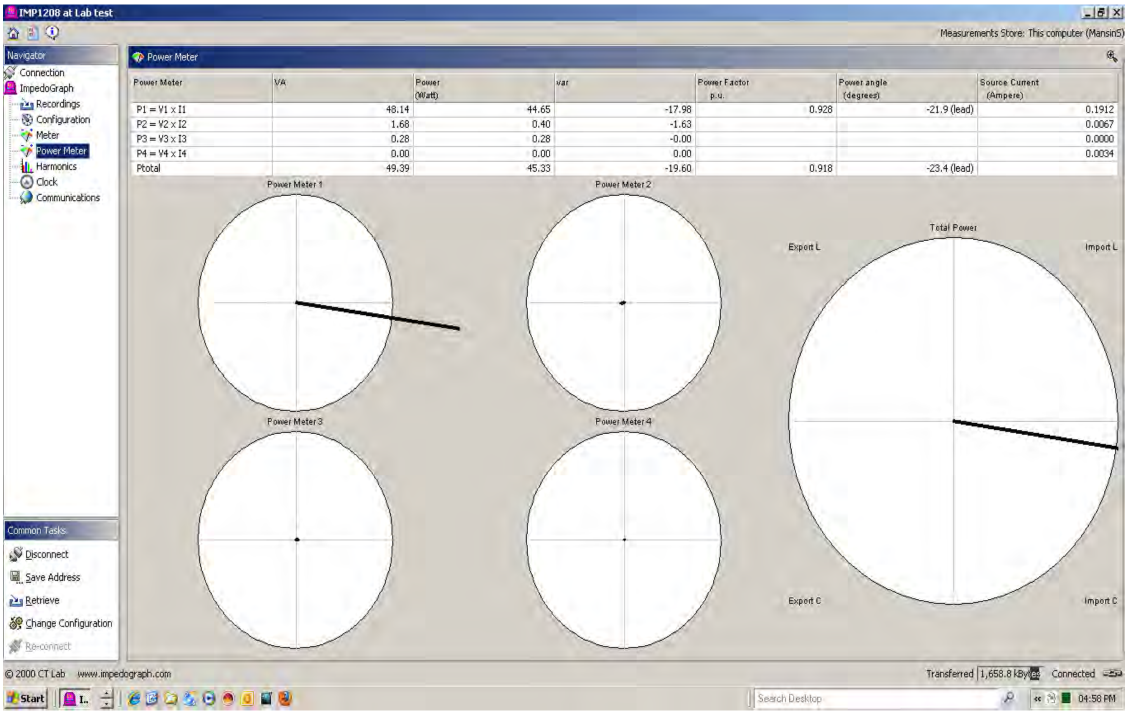
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	109.4%	251.68	0.0	0.188	7.7	-7.7 (lead)
2	108.6%	249.78	-120.4	0.007		-121.6 (lead)
3	108.2%	248.81	120.2	0.000		119.0 (lag)
4	0.1%	0.34		0.003		

Frequency 50.00 Hz Vunbalance 0.7% Iunbalance 100.0%

Figure 3-13 Voltage and Current Waveforms for HPF CFL

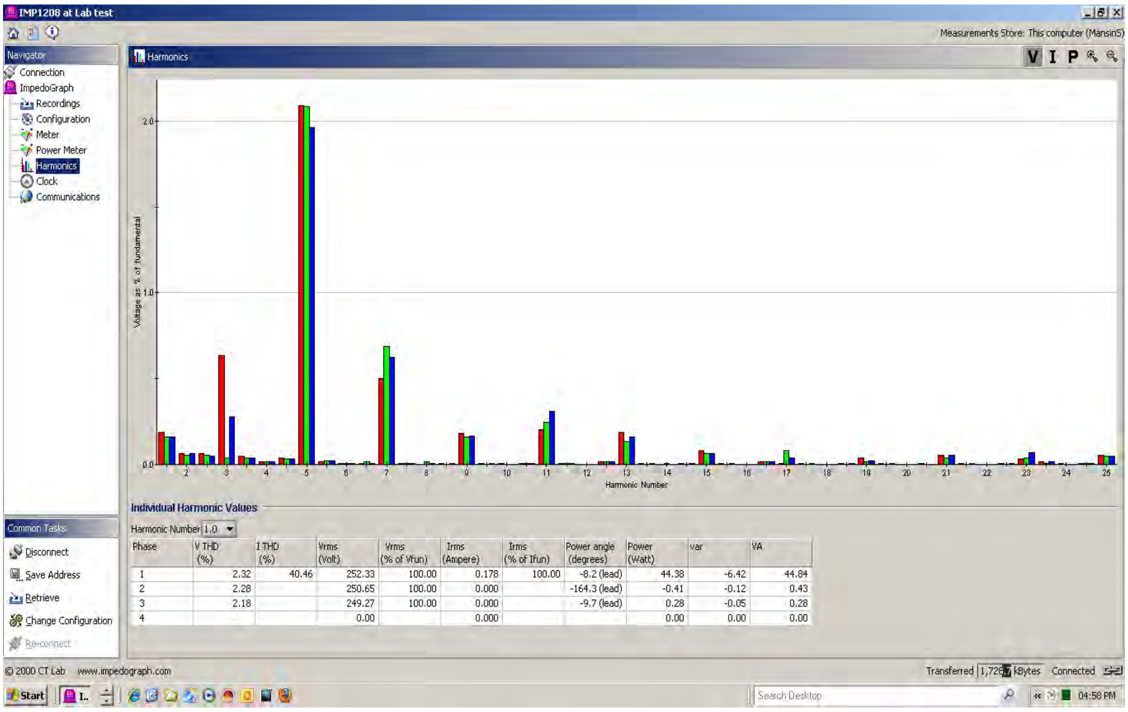
In figure 3-13 above, unlike the incandescent light bulb it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow at about 15º, peaking at about 75º and stops flowing at zero crossing at about 150º. There is a minimum load connected to the 2nd and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure below shows that the load measured has a high power factor of 0.928 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This should assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	48.14	44.65	-17.98	0.928	-21.9 (lead)	0.1912
P2 = V2 x I2	1.68	0.40	-1.63			0.0067
P3 = V3 x I3	0.28	0.28	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	49.39	45.33	-19.60	0.918	-23.4 (lead)	

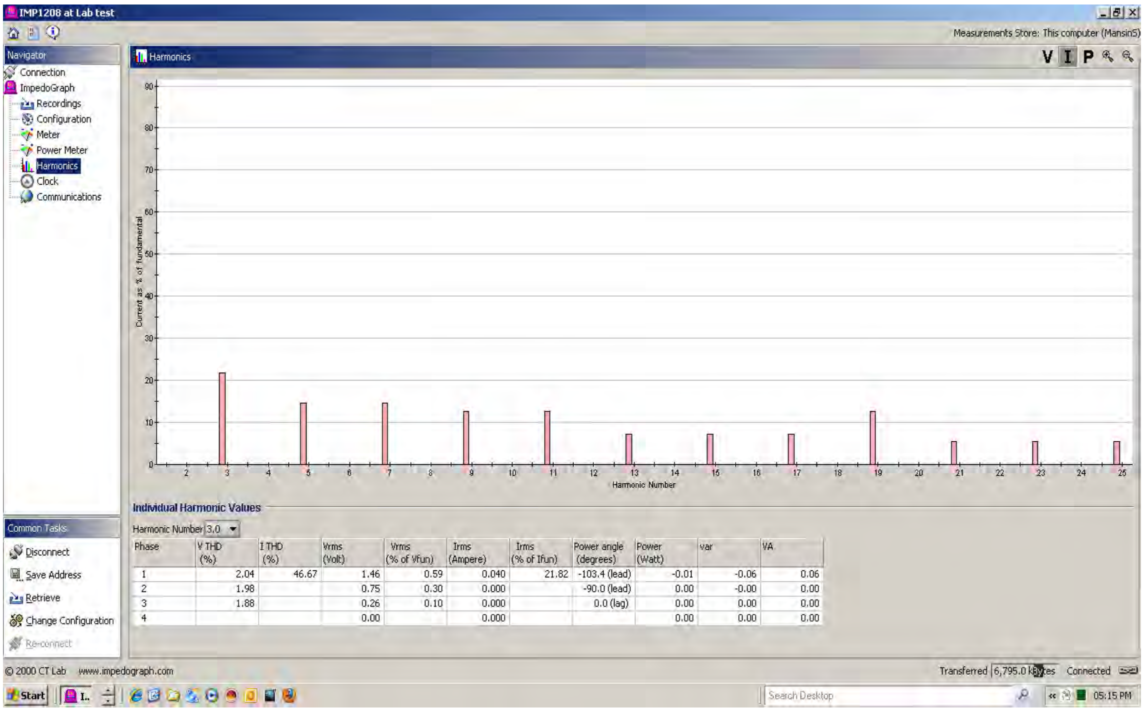
Figure 3-14 Power Meter Readings for HPF CFL



Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.32	40.46	252.33	100.00	0.178	100.00	-8.2 (lead)	44.38	-6.42	44.84
2	2.28		250.65	100.00	0.000		-164.3 (lead)	-0.41	-0.12	0.43
3	2.18		249.27	100.00	0.000		-9.7 (lead)	0.28	-0.05	0.28
4			0.00		0.000			0.00	0.00	0.00

Figure 3-15 Voltage Harmonics for HPF CFL

In figure 3-15 above, the voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic increasing from 1.8% to just over 2.0% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just under 2.3%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.04	46.67	1.46	0.59	0.040	21.82	-103.4 (lead)	-0.01	-0.06	0.06
2	1.98		0.75	0.30	0.000		-90.0 (lead)	0.00	-0.00	0.00
3	1.88		0.26	0.10	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-16 Current Harmonics for HPF CFL

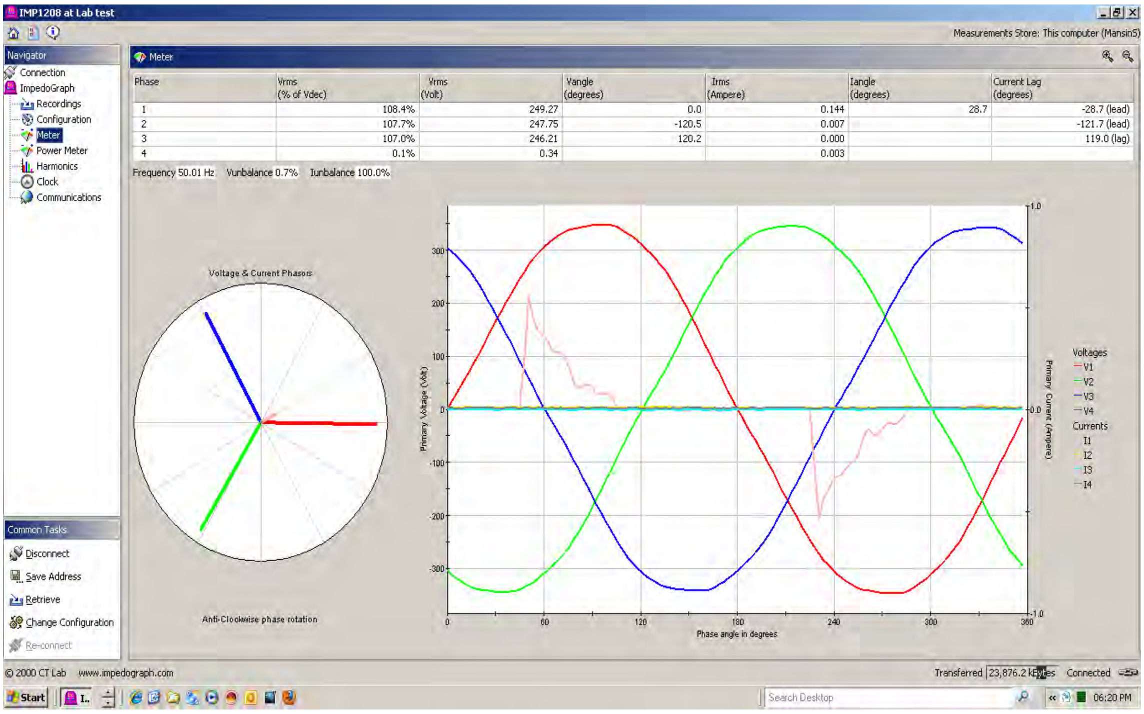
In figure 3-16 above, the current harmonics observed to be highest at the 3rd harmonic at 21.8% of the fundamental followed by the 5th, 7th, 9th,11th and 19th harmonics to be between 12%-15% of the fundamental and the rest are well under 10% of the fundamental. The THD is observed to be at 46.7 % of the fundamental current.

From the current harmonic spectrum observed, the 3rd harmonic to be within the IEC 61000-3-2 limit of 78.2% followed by the 5th , 7th, 9th,11th and 19th harmonic which are well within the IEC standard. The IEC expects THD to be within the 33 % limit while many US utilities implementing large scale Energy Efficiency programmes expects these lamps to be within 20% and this means that this lamp despite the excellent performance fails the IEC THD limit for current by 13%.

This HPF CFL lamp with acceptable lower harmonic characteristics should also be the same for lower wattage (11W-20W) HPF CFL and hence HPF CFLs can be recommended as technically suitable for large scale efficient lamp rollout programmes including large scale sustainability programmes for lower income homes if the cost benefit makes it viable.

3.4.4 Laboratory Test Results : Compact Flourescent Lamp (Eurolux, 20W)

This LPF CFL is a typical CFL used for domestic application replacement for a 100W incandescent (IL). The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



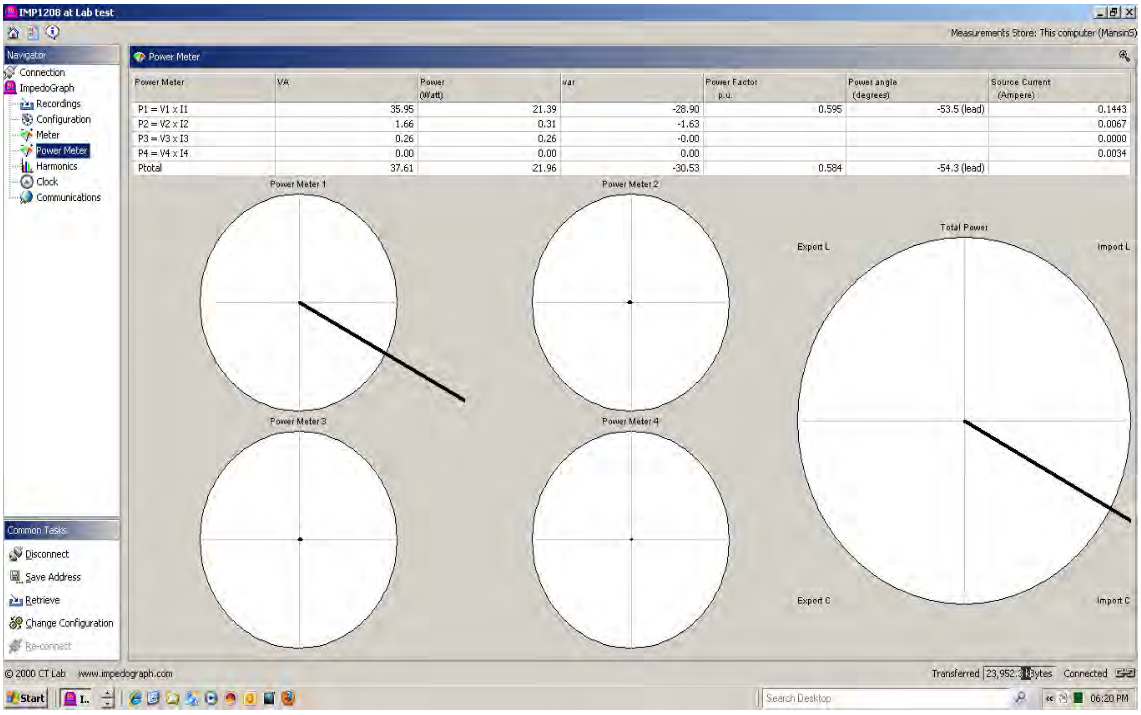
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.4%	249.27	0.0	0.144	28.7	-28.7 (lead)
2	107.7%	247.75	-120.5	0.007		-121.7 (lead)
3	107.0%	246.21	120.2	0.000		119.0 (lag)
4	0.1%	0.34		0.003		

Frequency 50.01 Hz Vunbalance 0.7% Iunbalance 100.0%

Figure 3-17 Voltage and Current Waveforms for Eurolux 20W CFL

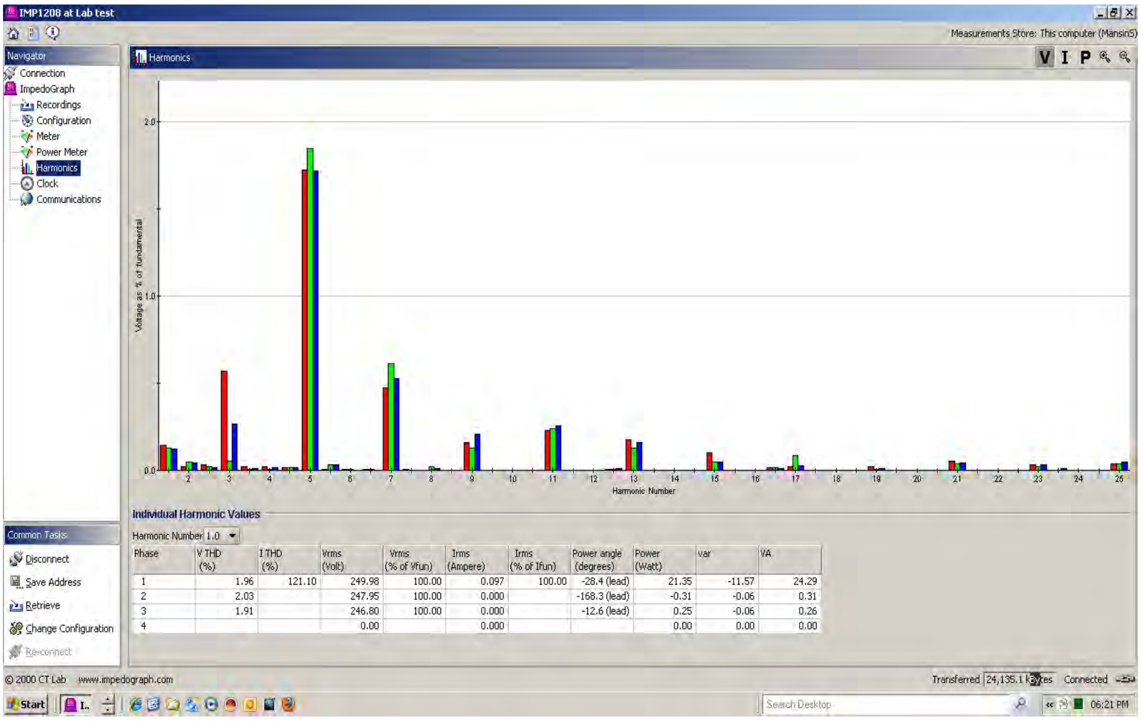
In figure 3-17 above, it is expected that I1 to be a distorted waveform as a result of being a non-linear device. I1 commences flow just before 45º, peaking just after 45º and stops flowing at zero crossing at about 105º. There is minimum load (measurement equipment) connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure below shows that the load measured has a standard power factor of 0.595 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This could assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	35.95	21.39	-28.90	0.595	-53.5 (lead)	0.1443
P2 = V2 x I2	1.66	0.31	-1.63			0.0067
P3 = V3 x I3	0.26	0.26	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	37.61	21.96	-30.53	0.584	-54.3 (lead)	

Figure 3-18 Power Meter Readings Observed for Eurolux 20W CFL



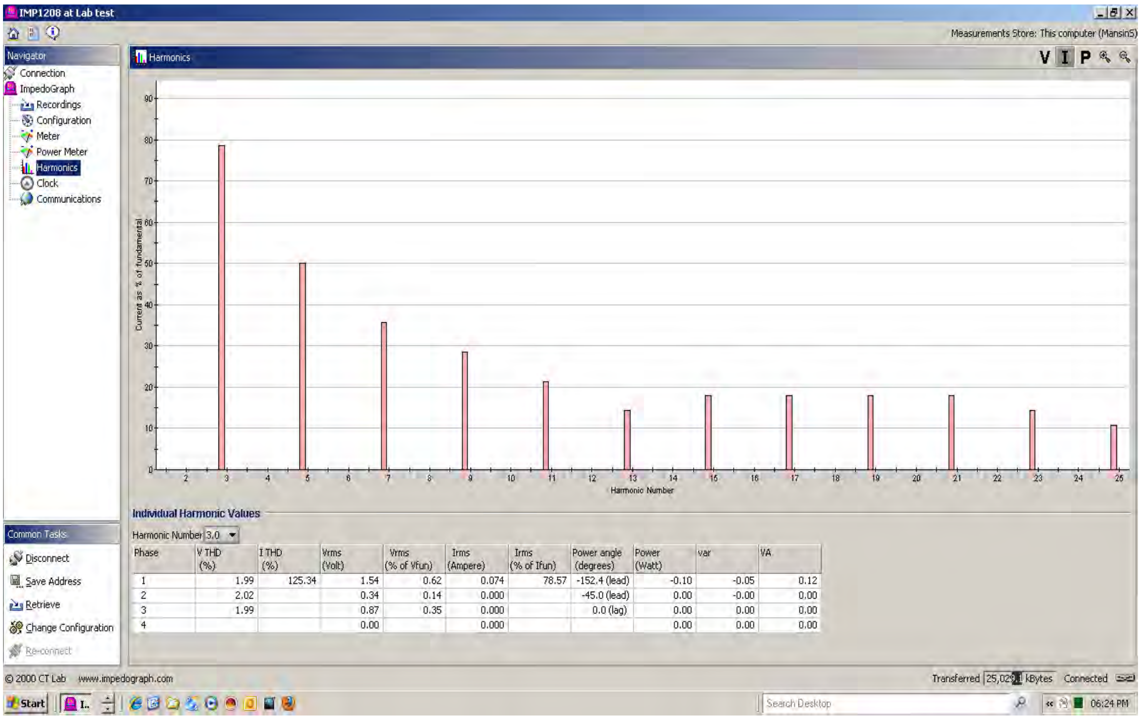
Individual Harmonic Values

Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	1.96	121.10	249.98	100.00	0.097	100.00	-28.4 (lead)	21.35	-11.57	24.29
2	2.03		247.95	100.00	0.000		-168.3 (lead)	-0.31	-0.06	0.31
3	1.91		246.80	100.00	0.000		-12.6 (lead)	0.25	-0.06	0.26
4			0.00		0.000			0.00	0.00	0.00

Figure 3-19 Voltage Harmonics for Eurolux 20W CFL

In figure 3-19 above, the voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic of about 1.8% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just under 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	1.99	125.34	1.54	0.62	0.074	78.57	-152.4 (lead)	-0.10	-0.05	0.12
2	2.02		0.34	0.14	0.000		-45.0 (lead)	0.00	-0.00	0.00
3	1.99		0.87	0.35	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-20 Current Harmonics for Eurolux 20W CFL

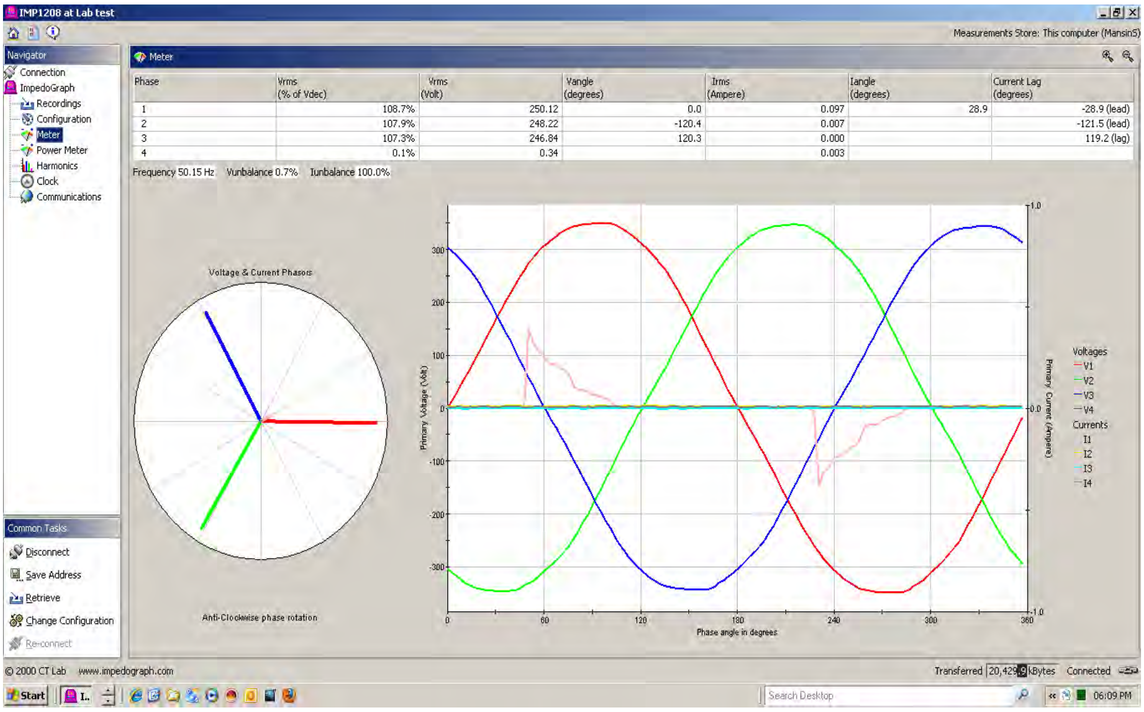
In figure 3-20 above, the current harmonics observed to be highest at the 3rd harmonic at 78.6% of the fundamental followed by the 5th, 7th, 9th and then the 11th harmonic. The rest of the graph up to the 25th harmonic are ranging between 10%-20%. The THD is observed to be at 125.3 % of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic to be just outside the IEC 61000-3-2 current harmonic limit of 78.2% and the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within the 33 % limit while many US utilities implementing large scale Energy Efficiency programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 92%.

This lamp is not compliant with the IEC 61000-3-2 current harmonic limitations and may pose a harmonic limit violations on networks already close to its limit. It is therefore not recommended for use in large scale efficient lighting rollout programmes without consultation with the respective distribution network engineer responsible for QOS.

3.4.5 Laboratory Test Results : Compact Flourescent Lamp (LeeLite, 15W)

This is a LPF CFL previously used for large scale residential efficient lighting rollouts as a replacement for a 60W incandescent (GLS). The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



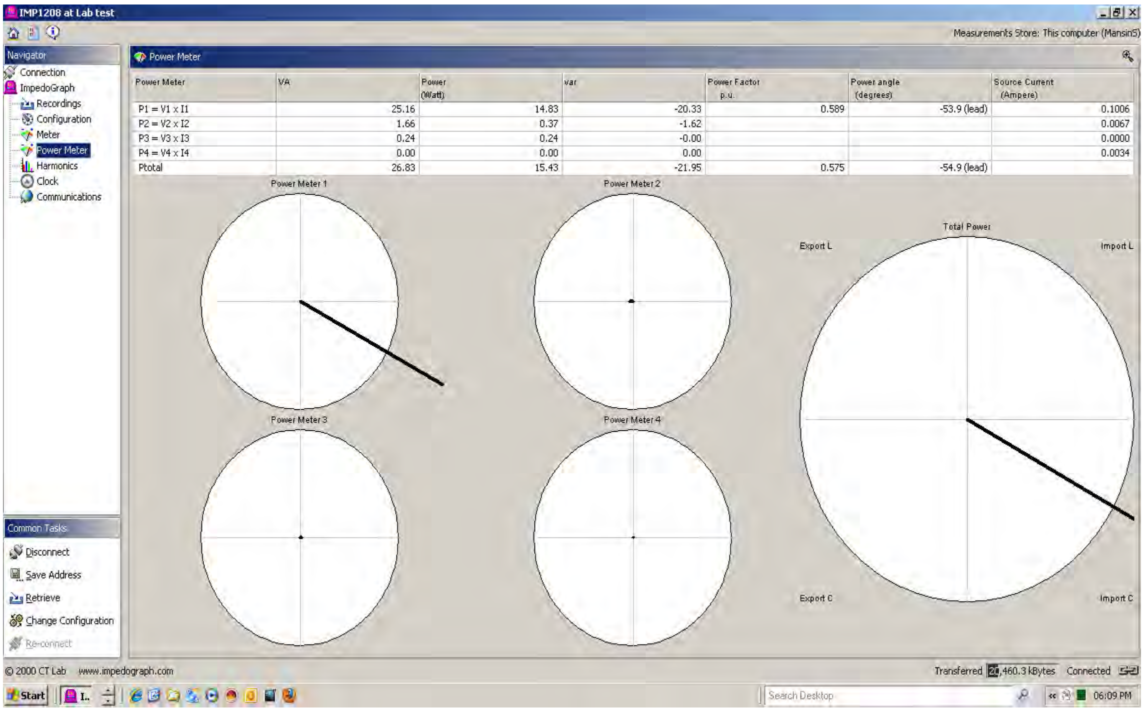
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.7%	250.12	0.0	0.097	28.9	-28.9 (lead)
2	107.9%	248.22	-120.4	0.007		-121.5 (lead)
3	107.3%	246.84	120.3	0.000		119.2 (lag)
4	0.1%	0.34		0.003		

Frequency 50.15 Hz Vunbalance 0.7% Iunbalance 100.0%

Figure 3-21 Voltage and Current Waveforms for LeeLite 15W CFL

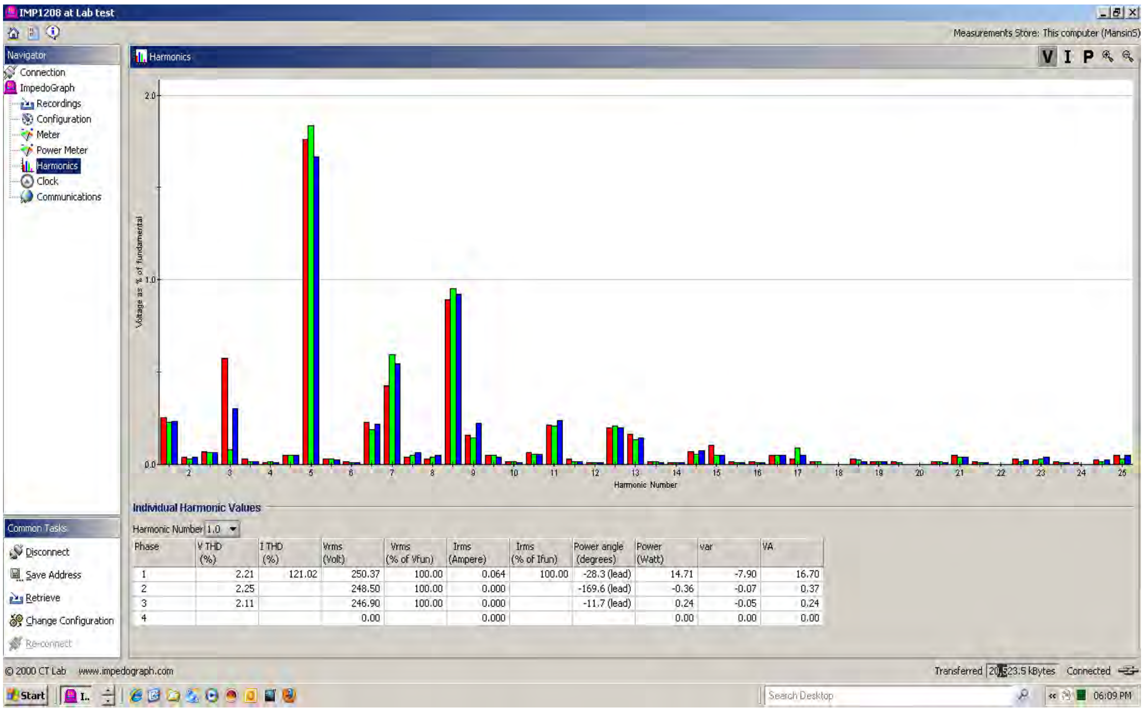
In figure 3-21 above, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 45º, peaking just after 45º and stops flowing at zero crossing at about 105º. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure 3-22 shows that the load measured has a standard power factor of 0.589 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This leading PF should assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	25.16	14.83	-20.33	0.589	-53.9 (lead)	0.1006
P2 = V2 x I2	1.66	0.37	-1.62			0.0067
P3 = V3 x I3	0.24	0.24	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	26.83	15.43	-21.95	0.575	-54.9 (lead)	

Figure 3-22 Power Meter Readings for LeeLite 15W CFL



Individual Harmonic Values

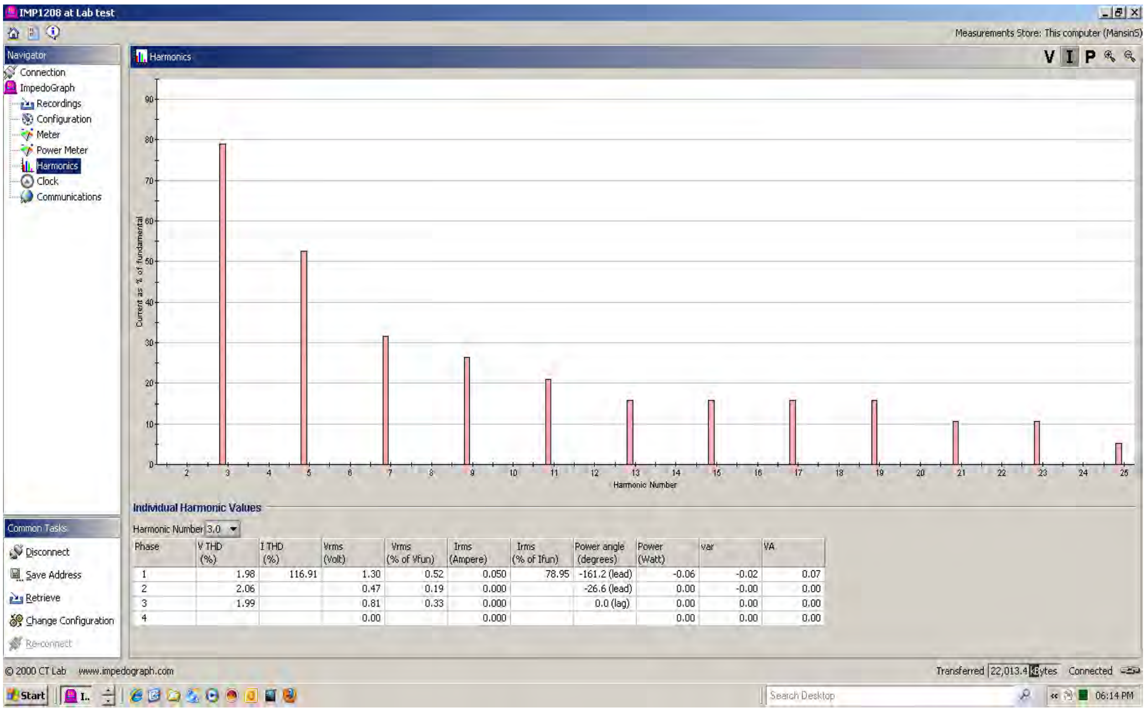
Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.21	121.02	250.37	100.00	0.064	100.00	-28.3 (lead)	14.71	-7.90	16.70
2	2.25		248.50	100.00	0.000		-169.6 (lead)	-0.36	-0.07	0.37
3	2.11		246.90	100.00	0.000		-11.7 (lead)	0.24	-0.05	0.24
4			0.00		0.000			0.00	0.00	0.00

Figure 3-23 Voltage Harmonics for LeeLite 15W CFL

In figure 3-23 above, the voltage harmonic spectrum observed is very similar to the main supply without load i.e. it has a very noticeable 5th harmonic of about 1.8% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. However, in addition, it is noted with concern that 9th harmonic moved from 0.25% to almost 1.0% and that while only

2nd and 4th harmonics were noticeable, it is noted that the rest of the even harmonics start to become visible. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just under 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	1.98	116.91	1.30	0.52	0.050	78.95	-161.2 (lead)	-0.06	-0.02	0.07
2	2.06		0.47	0.19	0.000		-26.6 (lead)	0.00	-0.00	0.00
3	1.99		0.81	0.33	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-24 Current Harmonics for LeeLite 15W CFL

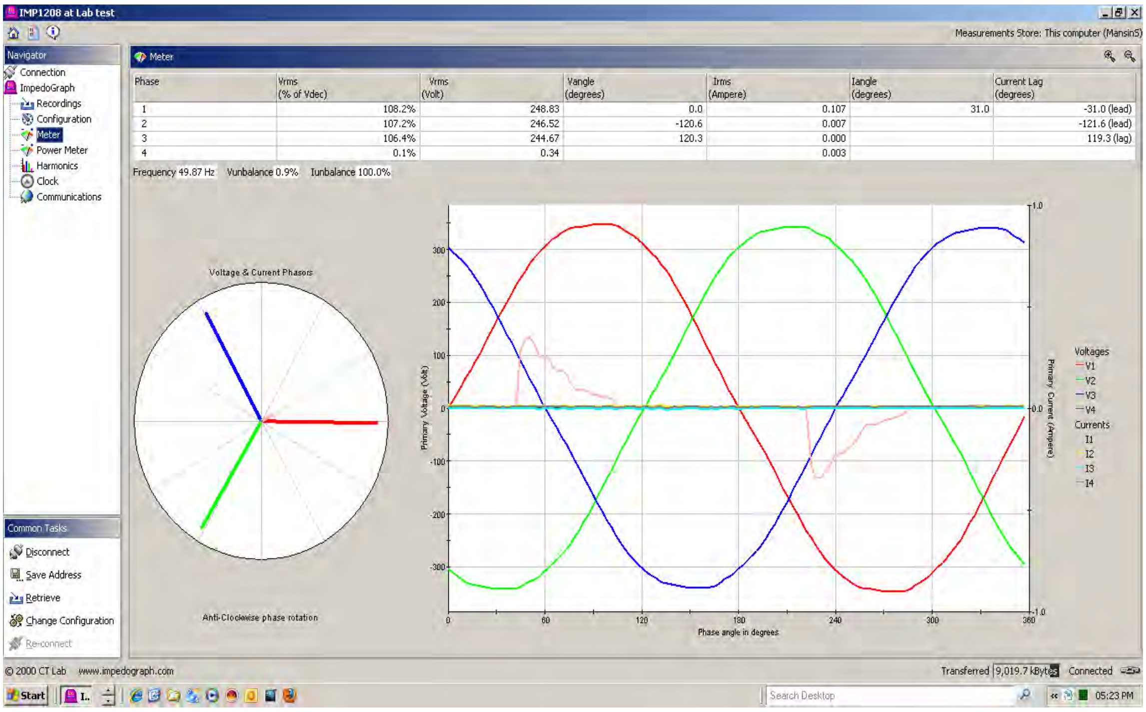
In figure 3-24 above, the current harmonics observed to be highest at the 3rd harmonic at 78.95% of the fundamental followed by the 5th, 7th, 9th and then the 11th harmonic. The rest on the graph up to the 23th harmonic are ranging between 10%-20% and 25th harmonic just above 5%. The THD is observed to be at 116.9 % of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic to be just outside the IEC 61000-3-2 limit of 78.2% and the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within the 33 % limit while many US utilities implementing large scale efficiency lighting programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 83%.

This lamp is not compliant to IEC 61000-3-2 current harmonic limitations and may pose a risk to harmonic limits on networks already close to its limit. It is therefore not recommended for use in large scale efficient lighting rollout programmes without consultation with the respective distribution network engineer responsible for QOS.

3.4.6 Laboratory Test Results : Compact Flourescent Lamp (Megaman, 9W)

This is a certified premium quality LPF CFL that is a typical domestic application replacement for a 40W incandescent (GLS). The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



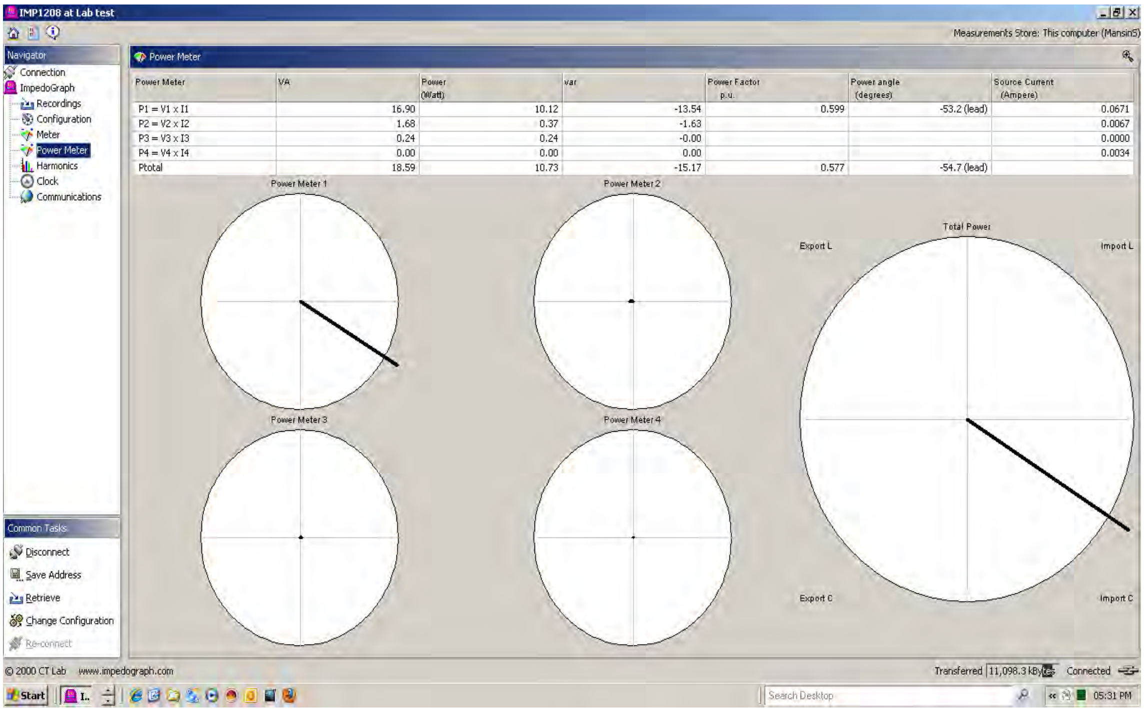
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.2%	248.83	0.0	0.107	31.0	-31.0 (lead)
2	107.2%	246.52	-120.6	0.007		-121.6 (lead)
3	106.4%	244.67	120.3	0.000		119.3 (lag)
4	0.1%	0.34		0.003		

Frequency 49.87 Hz Vunbalance 0.9% Iunbalance 100.0%

Figure 3-25 Voltage and Current Waveforms for Megaman 9W CFL

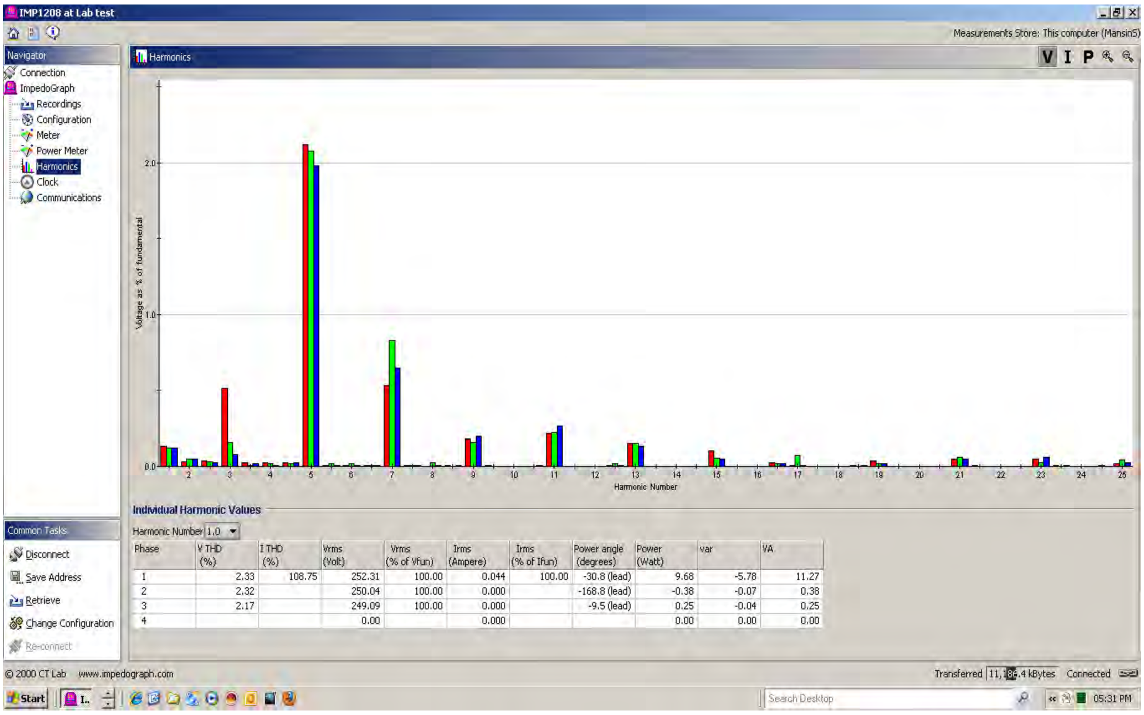
In figure 3-25 above, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 45°, peaking just after 45° and stops flowing at zero crossing at about 105°. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure below shows that the load measured has a standard power factor of 0.599 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This could assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	16.90	10.12	-13.54	0.599	-53.2 (lead)	0.0671
P2 = V2 x I2	1.68	0.37	-1.63			0.0067
P3 = V3 x I3	0.24	0.24	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	18.59	10.73	-15.17	0.577	-54.7 (lead)	

Figure 3-26 Power Meter Readings for Megaman 9W CFL



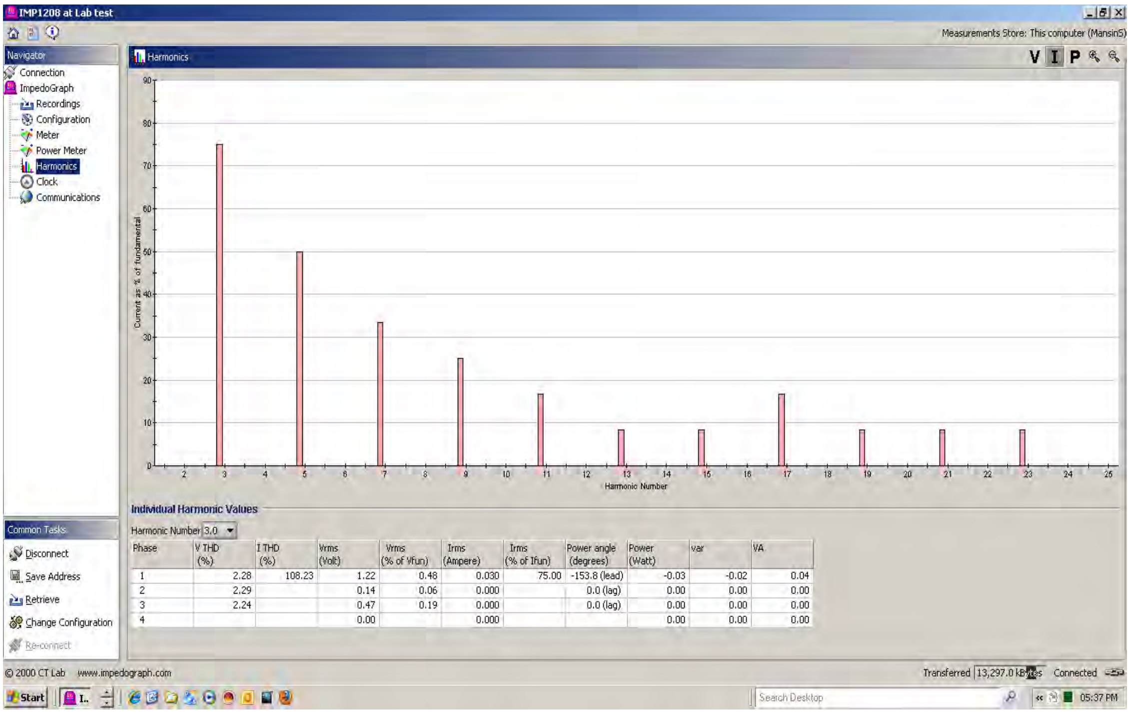
Individual Harmonic Values

Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.33	108.75	252.31	100.00	0.044	100.00	-30.8 (lead)	9.68	-5.78	11.27
2	2.32		250.04	100.00	0.000		-168.8 (lead)	-0.38	-0.07	0.38
3	2.17		249.09	100.00	0.000		-9.5 (lead)	0.25	-0.04	0.25
4			0.00		0.000			0.00	0.00	0.00

Figure 3-27 Voltage Harmonics for Megaman 9W CFL

In figure 3-27 above, the voltage harmonic spectrum observed is very similar to the mains supply without loading i.e. it has a very noticeable 5th harmonic that increased from about 1.8% to about 2.1% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just over 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.28	108.23	1.22	0.48	0.030	75.00	-153.8 (lead)	-0.03	-0.02	0.04
2	2.29		0.14	0.06	0.000		0.0 (lag)	0.00	0.00	0.00
3	2.24		0.47	0.19	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-28 Current Harmonics for Megaman 9W CFL

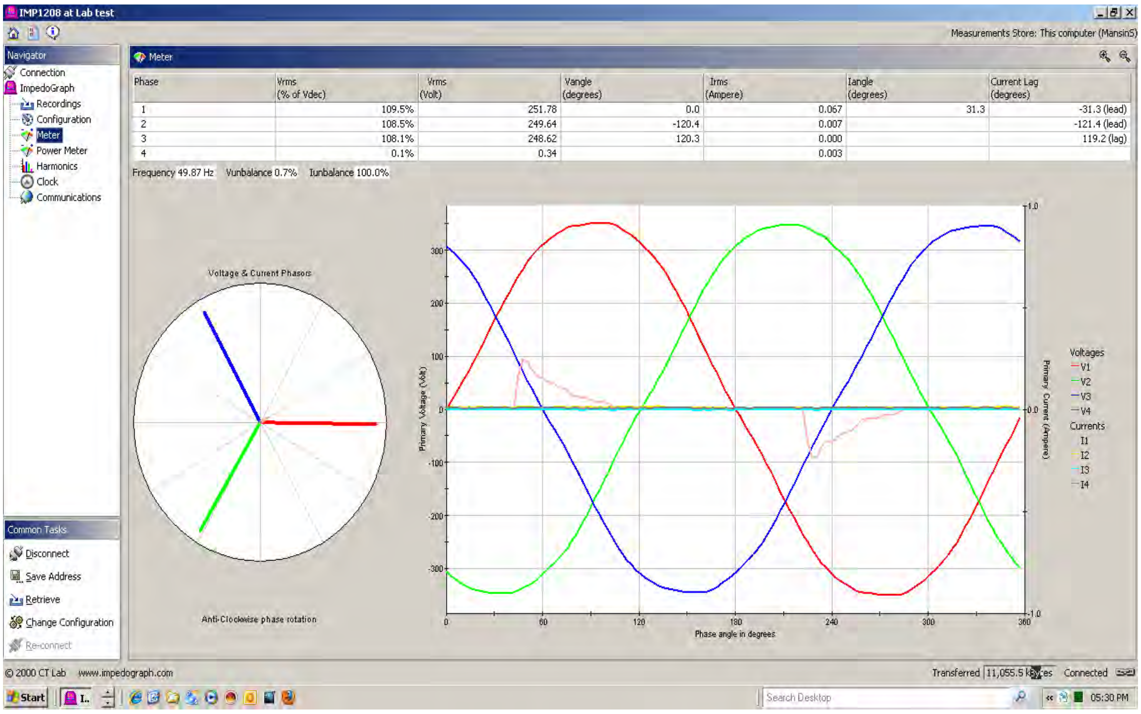
In figure 3-28 above, the current harmonics observed to be highest at the 3rd harmonic at 75.0% of the fundamental followed by the 5th which is about 50.0% while rest of the harmonics are above the minimum current harmonic limit up to the 11th harmonic. The rest on the graph from the 13th harmonic onwards are below 5% except for the 17th harmonic which in between 10% and 20%. The THD is observed to be at 108.7% of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic to be within the IEC 61000-3-2 harmonic current limits of 78.2% and the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within the 33 % limit while many utilities implementing large scale Energy Efficiency programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 75%.

This lamp is not compliant to the IEC 61000-3-2 current harmonic limit and may pose a risk to the harmonic limits of a network that is already close to the limit. This lamp is not recommended for large scale efficient lighting rollout programmes without consultation with respective distribution network engineer responsible for QOS.

3.4.7 Laboratory Test Results : Compact Flourescent Lamp (Megaman, 15W)

This lamp is a certified premium quality LPF 15 W CFL that is a typical replacement for a 60W incandescent (GLS). The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



IMP1208 at Lab test

Measurements Store: This computer (Mansin5)

Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	109.5%	251.78	0.0	0.067	31.3	-31.3 (lead)
2	108.5%	249.64	-120.4	0.007		-121.4 (lead)
3	108.1%	248.62	120.3	0.000		119.2 (lag)
4	0.1%	0.34		0.003		

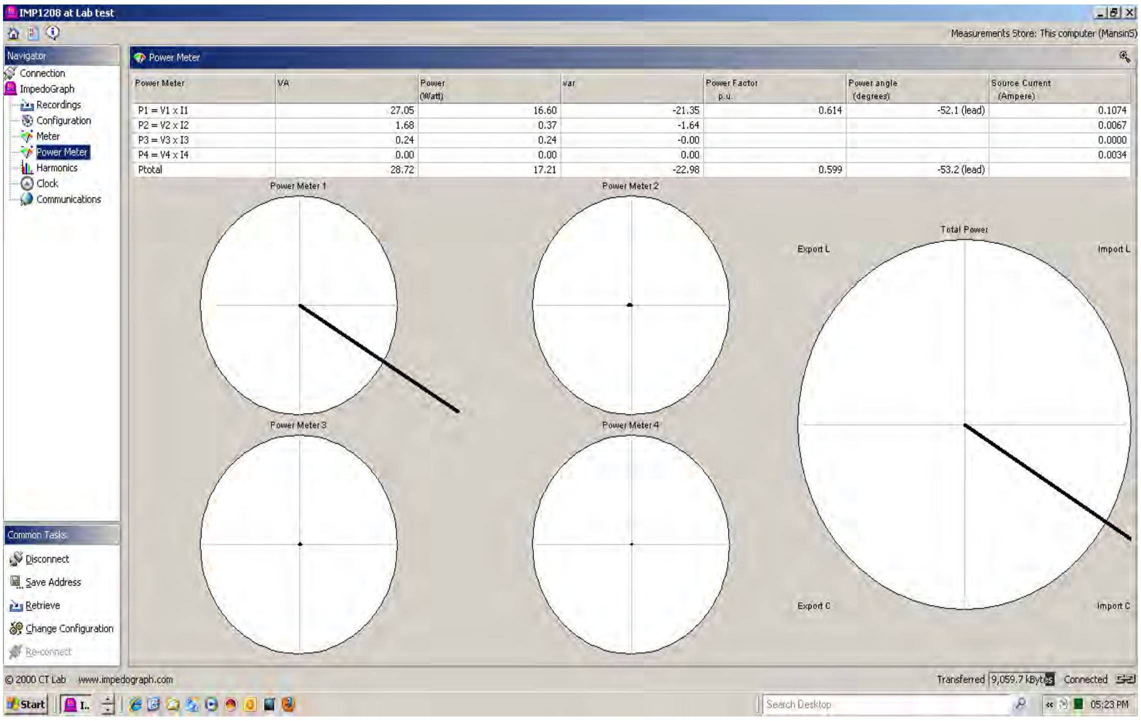
Frequency 49.87 Hz Vunbalance 0.7% Iunbalance 100.0%

Transferred 11,055.5 kBytes Connected

Figure 3-29 Voltage and Current Waveforms for Megaman 15W CFL

In figure 3-29, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 45º, peaking just after 45º and stops flowing at zero crossing at about 105º. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

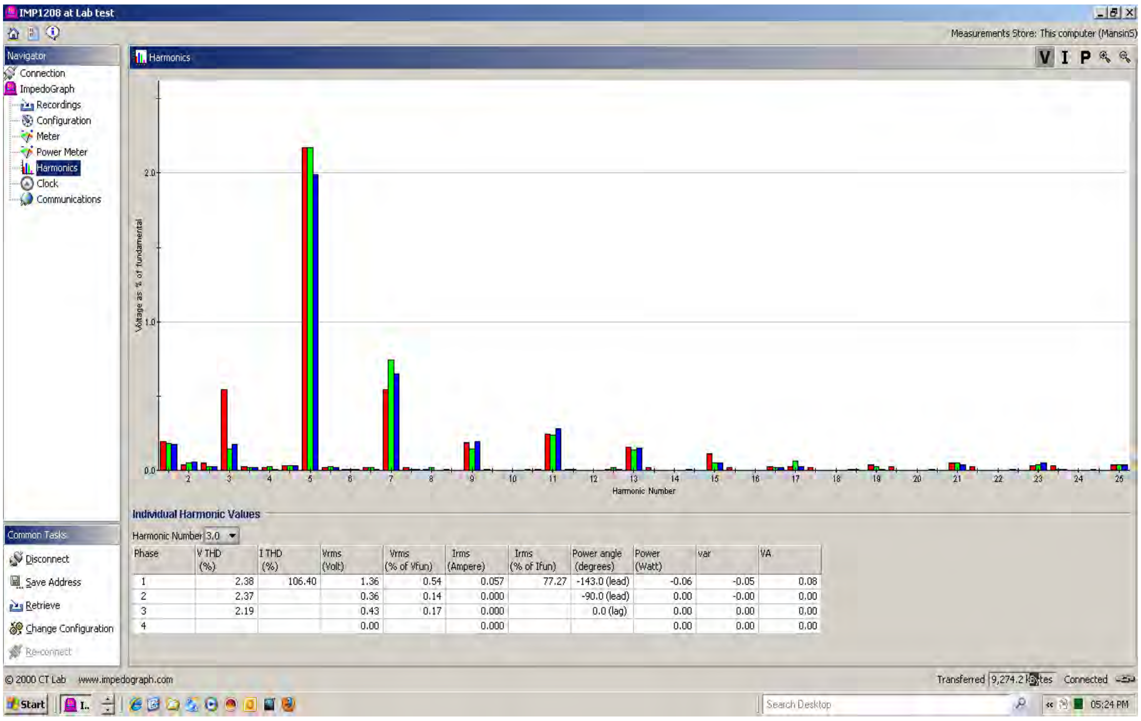
The figure below shows that the load measured has a standard power factor of 0.614 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This could assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter

Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	27.05	16.60	-21.35	0.614	-52.1 (lead)	0.1074
P2 = V2 x I2	1.68	0.37	-1.64			0.0067
P3 = V3 x I3	0.24	0.24	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	28.72	17.21	-22.98	0.599	-53.2 (lead)	

Figure 3-30 Power Meter Readings for Megaman 15W CFL



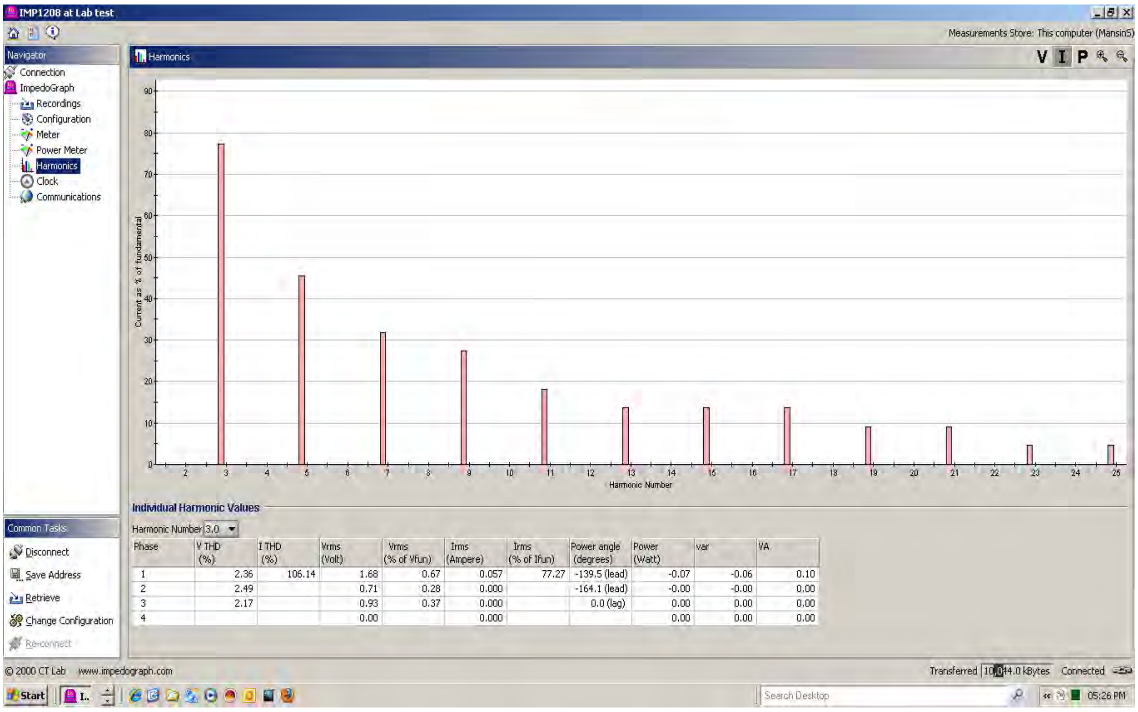
Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.38	106.40	1.36	0.54	0.057	77.27	-143.0 (lead)	-0.06	-0.05	0.08
2	2.37		0.36	0.14	0.000		-90.0 (lead)	0.00	-0.00	0.00
3	2.19		0.43	0.17	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-31 Voltage Harmonics for Megaman 15W CFL

In figure 3-31 above, the voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic that increased from about 1.8% to about 2.4% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just under 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.36	106.14	1.68	0.67	0.057	77.27	-139.5 (lead)	-0.07	-0.06	0.10
2	2.49		0.71	0.28	0.000		-164.1 (lead)	-0.00	-0.00	0.00
3	2.17		0.93	0.37	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-32 Current Harmonics for Megaman 15W CFL

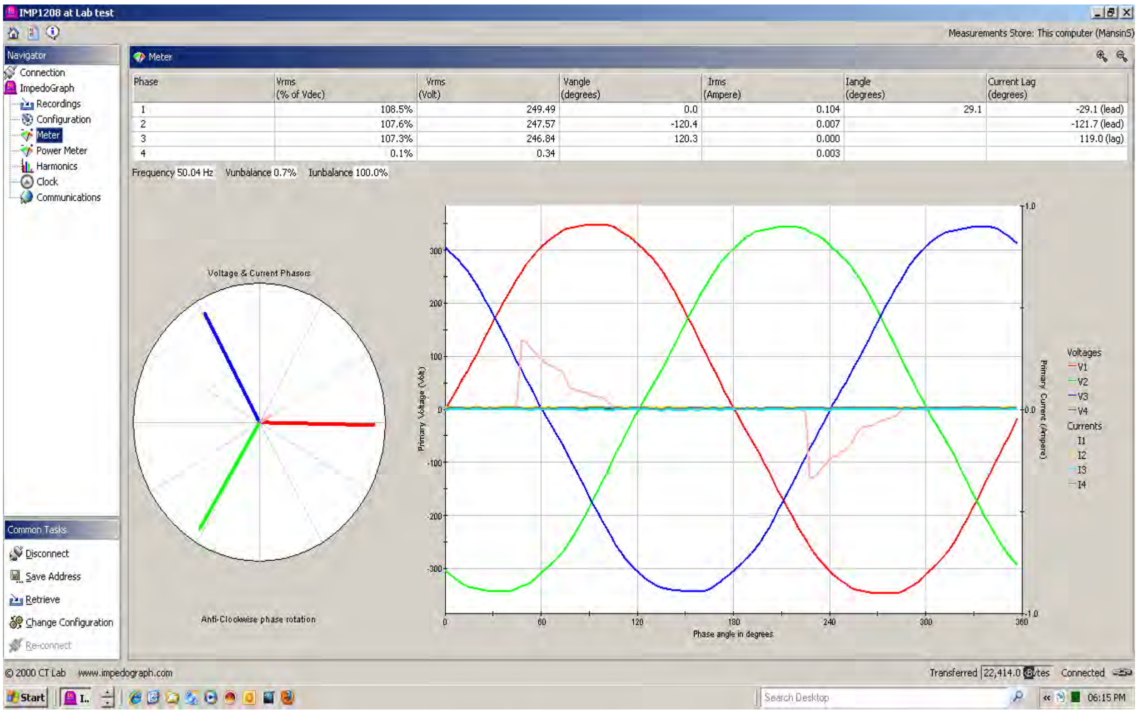
In figure 3-32 above, the current harmonics observed to be highest at the 3rd harmonic at 77.3% of the fundamental followed by the 5th which is at about 45.5% which is above the IEC limit while rest of the harmonics are above the minimum current harmonic limits up to the 17th harmonics. The rest on the graph from the 19th harmonic are below 10%. The THD is observed to be at 106.1 % of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic within the IEC 61000-3-2 harmonic current limits of 78.2% and the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within 33 % limit while many utilities implementing large scale Energy Efficiency programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 73%.

This lamp is not compliant with the IEC 61000-3-2 current harmonic limitations and may pose a risk to harmonic limits on specific networks already close to their limits. This CFL is not recommended for use in large scale efficient lighting rollout programmes without consultation with respective distribution network engineer responsible for QOS.

3.4.8 Laboratory Test Results : Compact Flourescent Lamp (Philips Genie, 14W)

This is a LPF 14 W CFL that is a typical domestic application replacement for a 60W incandescent (GLS). The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.5%	249.49	0.0	0.104	29.1	-29.1 (lead)
2	107.6%	247.57	-120.4	0.007		-121.7 (lead)
3	107.3%	246.84	120.3	0.000		119.0 (lag)
4	0.1%	0.34		0.003		

Frequency 50.04 Hz Vunbalance 0.7% Iunbalance 100.0%

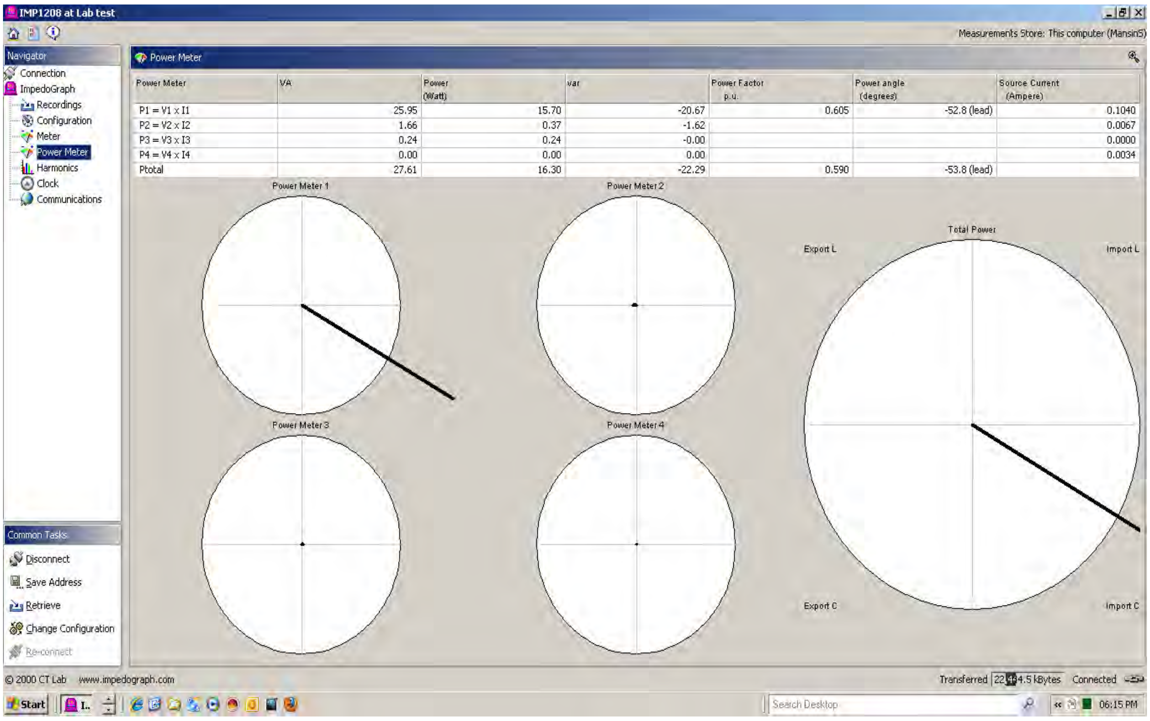
Measurements Store: This computer (MansinS)

Transferred 22,414.0 Bytes Connected

Figure 3-33 Voltage and Current Waveforms for Philips Genie 14W CFL

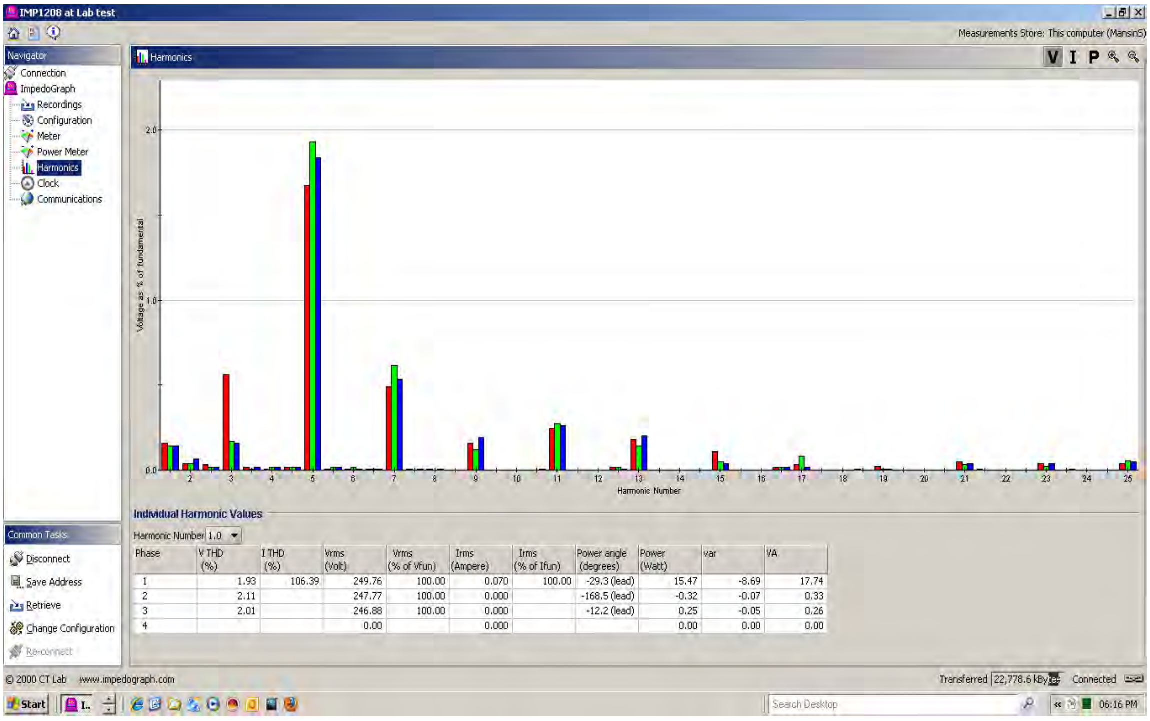
In figure 3-33 above, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 45º, peaking just after 45º and stops flowing at zero crossing at about 100º. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure below shows that the load measured has a standard power factor of 0.605 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This should assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	25.95	15.70	-20.67	0.605	-52.8 (lead)	0.1040
P2 = V2 x I2	1.66	0.37	-1.62			0.0067
P3 = V3 x I3	0.24	0.24	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	27.61	16.30	-22.29	0.590	-53.8 (lead)	

Figure 3-34 Power Meter Readings for Philips Genie 14W CFL



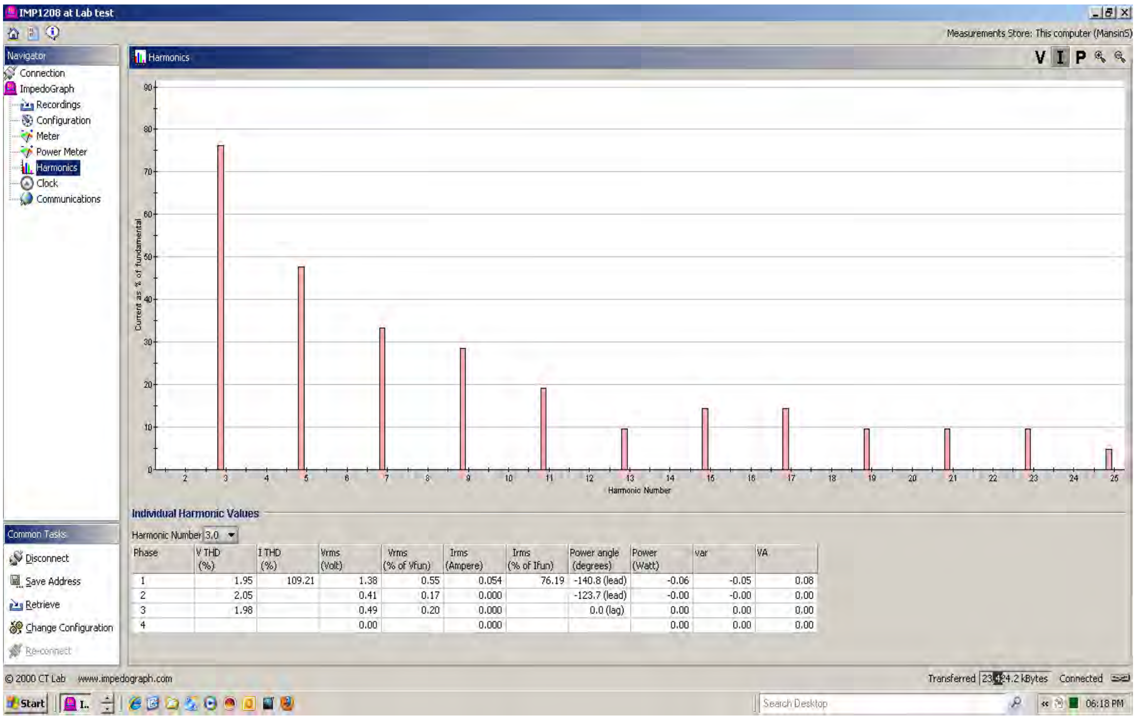
Individual Harmonic Values

Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	1.93	106.39	249.76	100.00	0.070	100.00	-29.3 (lead)	15.47	-8.69	17.74
2	2.11		247.77	100.00	0.000		-168.5 (lead)	-0.32	-0.07	0.33
3	2.01		246.88	100.00	0.000		-12.2 (lead)	0.25	-0.05	0.26
4			0.00		0.000			0.00	0.00	0.00

Figure 3-35 Voltage Harmonics for Philips Genie 14W CFL

In figure 3-35 above, the voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic that remains about 1.8% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just under 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	1.95	109.21	1.38	0.55	0.054	76.19	-140.8 (lead)	-0.06	-0.05	0.08
2	2.05		0.41	0.17	0.000		-123.7 (lead)	-0.00	-0.00	0.00
3	1.98		0.49	0.20	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-36 Current Harmonics for Philips Genie 14W CFL

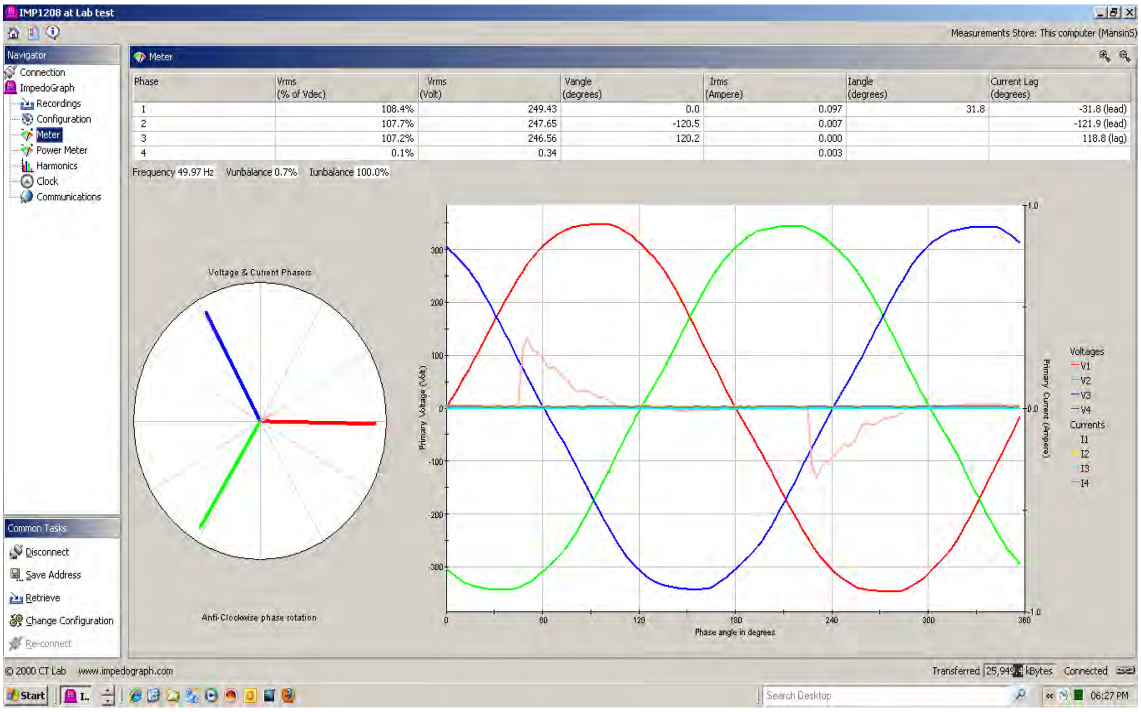
In figure 3-36 above, the current harmonics observed to be highest at the 3rd harmonic at 76.19% of the fundamental followed by the 5th which about 47.6% which is just above the IEC limit while rest of the harmonics are above the minimum current harmonic limits up to the 11th harmonics. The rest on the graph from the 13th harmonic are below 10% except for the 15th and 17th harmonic. The THD is observed to be at 106.4% of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic within the IEC 61000-3-2 harmonic current limits of 78.2% and the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within 33 % limit while many utilities implementing large scale energy efficiency programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 73%.

This lamp is not compliant to the IEC 61000-3-2 current harmonic limitation and may pose a risk to harmonic limits on networks already close to its limit. It is therefore not recommended for use in large scale efficient lighting rollout programmes without consultation with the respective distribution network engineer responsible for QOS.

3.4.9 Laboratory Test Results : Compact Flourescent Lamp (Eskom NFS, 14W)

This is a LPF 14 W CFL that is a typical domestic application replacement for a 60W incandescent (GLS). The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



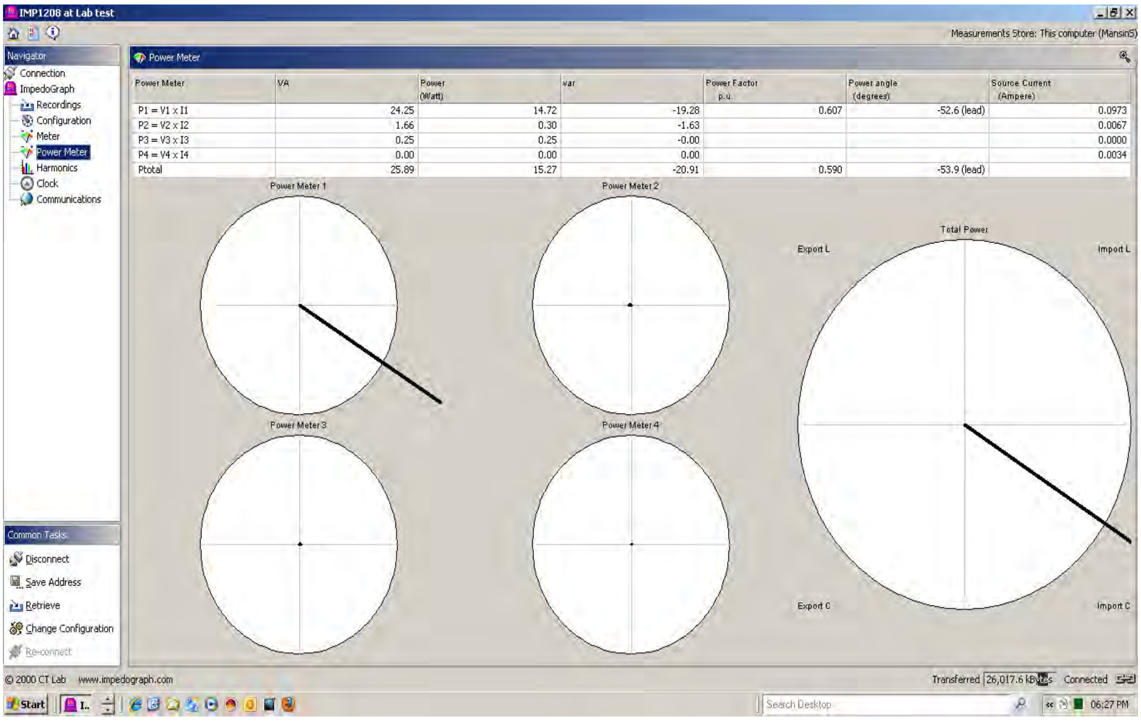
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.4%	249.43	0.0	0.097	31.8	-31.8 (lead)
2	107.7%	247.65	-120.5	0.007		-121.9 (lead)
3	107.2%	246.56	120.2	0.000		118.8 (lag)
4	0.1%	0.34		0.003		

Frequency 49.97 Hz Vunbalance 0.7% Iunbalance 100.0%

Figure 3-37 Voltage and Current Waveforms for Eskom NFS 14W CFL

In figure 3-37 above, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 45º, peaking just after 45º and stops flowing at zero crossing at about 100º. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

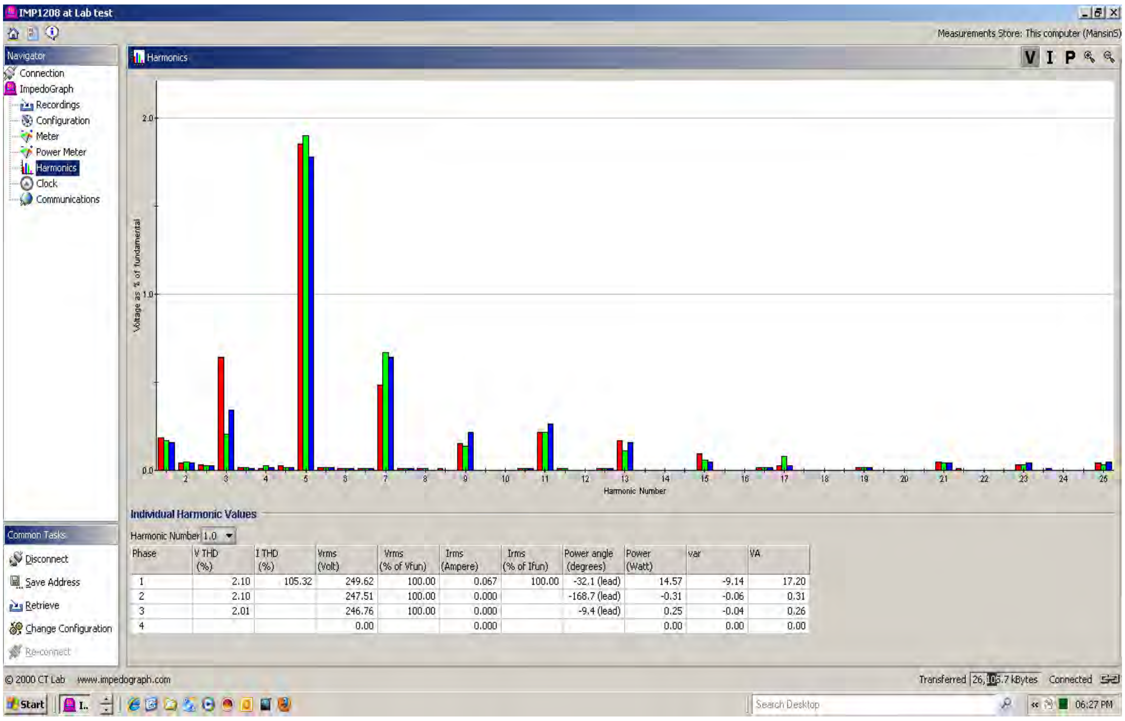
The figure below shows that the load measured has a standard power factor of 0.607 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This could assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter

Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	24.25	14.72	-19.28	0.607	-52.6 (lead)	0.0973
P2 = V2 x I2	1.66	0.30	-1.63			0.0067
P3 = V3 x I3	0.25	0.25	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	25.89	15.27	-20.91	0.590	-53.9 (lead)	

Figure 3-38 Power Meter Readings for Eskom NFS 14W CFL



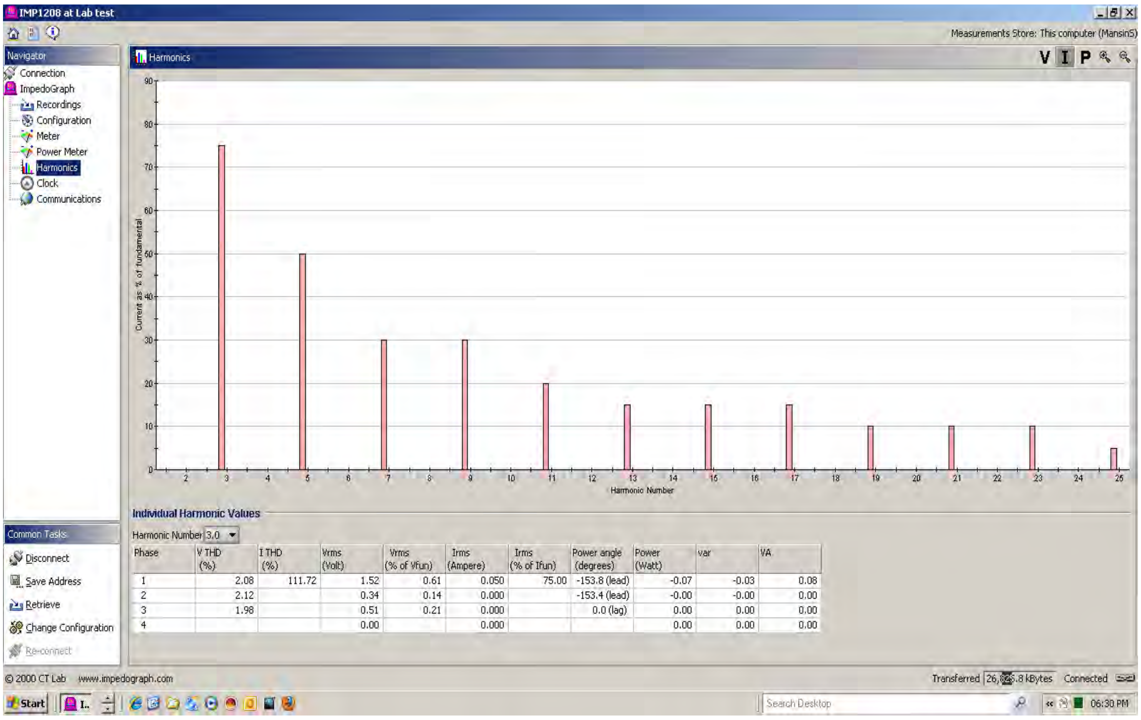
Individual Harmonic Values

Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.10	105.32	249.62	100.00	0.067	100.00	-32.1 (lead)	14.57	-9.14	17.20
2	2.10		247.51	100.00	0.000		-168.7 (lead)	-0.31	-0.06	0.31
3	2.01		246.76	100.00	0.000		-9.4 (lead)	0.25	-0.04	0.26
4			0.00		0.000			0.00	0.00	0.00

Figure 3-39 Voltage Harmonics for Eskom NFS 14W CFL

The voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic that remains about 1.8% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just over 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.08	111.72	1.52	0.61	0.050	75.00	-153.8 (lead)	-0.07	-0.03	0.08
2	2.12		0.34	0.14	0.000		-153.4 (lead)	-0.00	-0.00	0.00
3	1.98		0.51	0.21	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-40 Current Harmonics for Eskom NFS 14W CFL

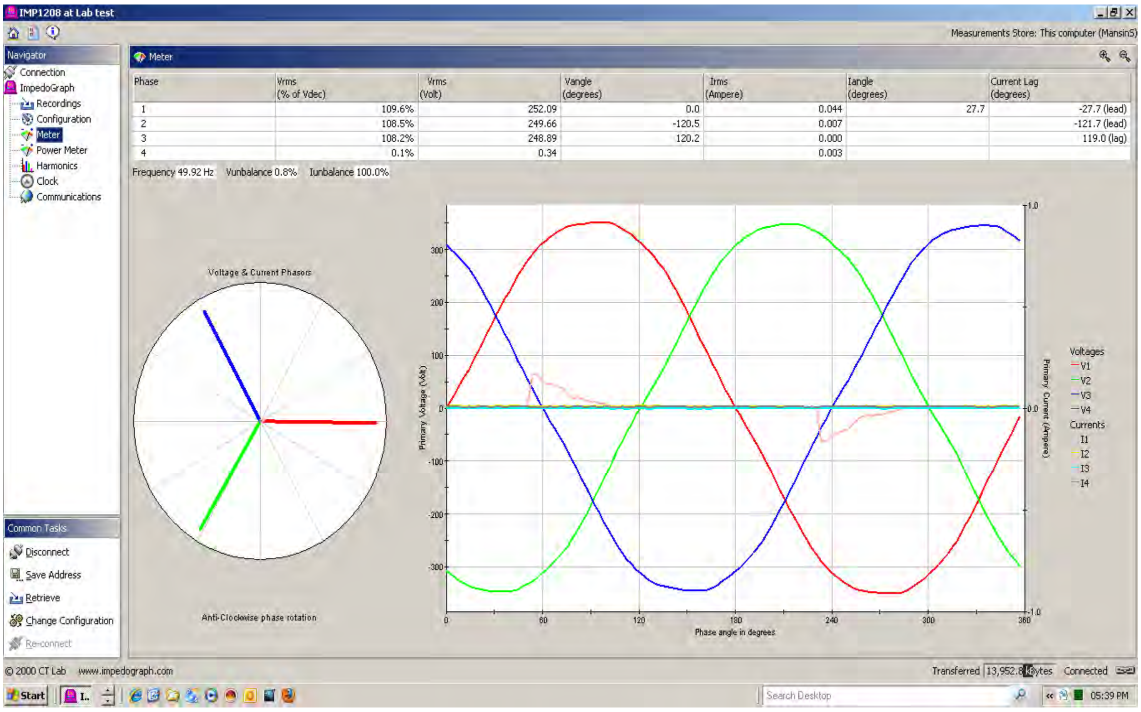
In figure 3-40 above, the current harmonics observed to be highest at the 3rd harmonic at 75.0% of the fundamental followed by the 5th which about 50.0% and just above the IEC limit while rest of the harmonics are above the minimum current harmonic limits up to the 17th harmonics. The rest on the graph from the 19th harmonic are below 10%. The THD is observed to be at 105.3% of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic within the IEC 61000-3-2 current harmonic limitation of 78.2% and the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within the 33 % limit while many utilities implementing large scale Energy Efficiency programmes expect these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 73%.

This lamp is not compliant with the IEC 61000-3-2 current harmonic limitations and may pose a risk to harmonic limits on networks already close to its limit. It is therefore not recommended for use in large scale efficient lighting rollout programmes without consultation with the respective distribution network engineer responsible for QOS.

3.4.10 Laboratory Test Results : Compact Flourescent Lamp (Pila, 15W)

This is a LPF 15 W CFL that is a typical domestic application replacement for a 60W incandescent (GLS. The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains



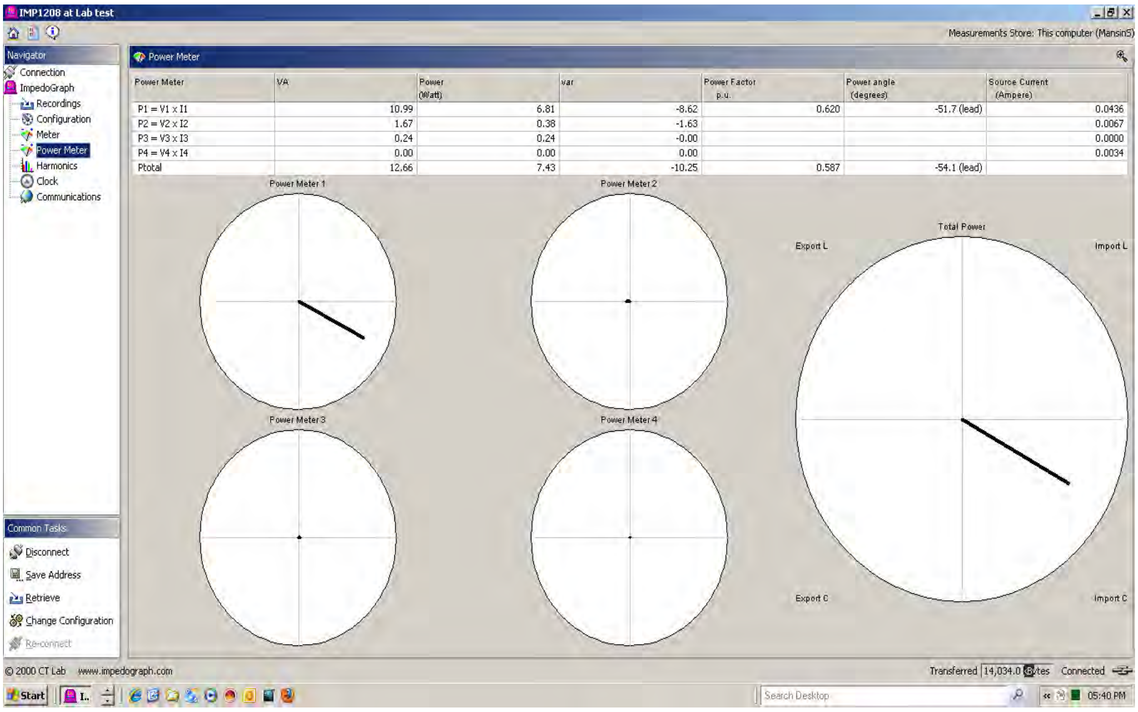
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	109.6%	252.09	0.0	0.044	27.7	-27.7 (lead)
2	108.5%	249.66	-120.5	0.007		-121.7 (lead)
3	108.2%	248.89	120.2	0.000		119.0 (lag)
4	0.1%	0.34		0.003		

Frequency 49.92 Hz Vunbalance 0.8% Iunbalance 100.0%

Figure 3-41 Voltage and Current Waveforms for Pila 15W CFL

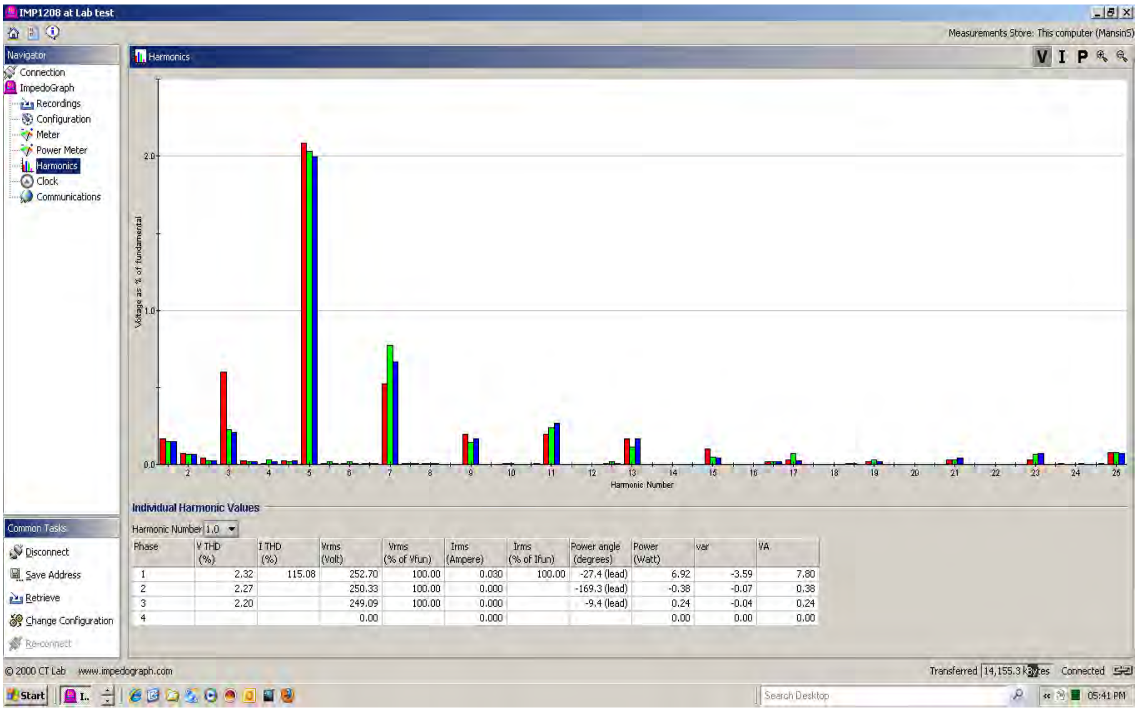
As observed in figure 3-41 above, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 48º, peaking just after 48º and stops flowing at zero crossing at about 100º. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure below shows that the load measured has a standard power factor of 0.620 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This should assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	10.99	6.81	-8.62	0.620	-51.7 (lead)	0.0436
P2 = V2 x I2	1.67	0.38	-1.63			0.0067
P3 = V3 x I3	0.24	0.24	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	12.66	7.43	-10.25	0.587	-54.1 (lead)	

Figure 3-42 Power Meter Readings for Pila 15W CFL



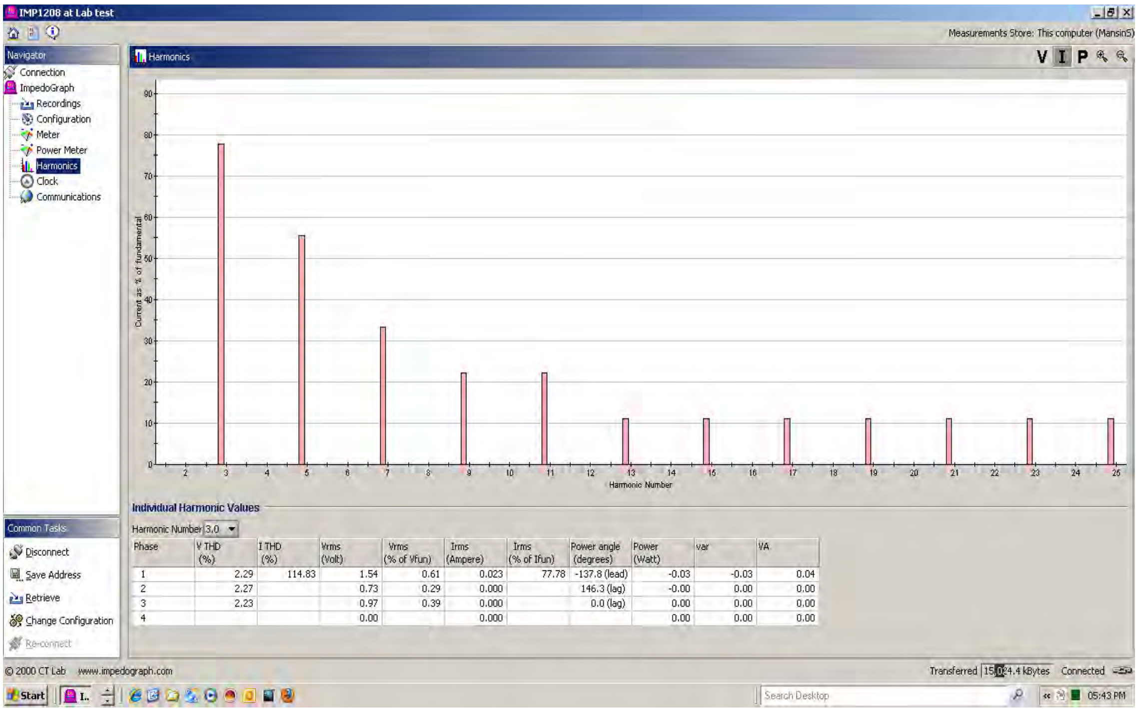
Individual Harmonic Values

Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.32	115.08	252.70	100.00	0.030	100.00	-27.4 (lead)	6.92	-3.59	7.80
2	2.27		250.33	100.00	0.000		-169.3 (lead)	-0.38	-0.07	0.38
3	2.20		249.09	100.00	0.000		-9.4 (lead)	0.24	-0.04	0.24
4			0.00		0.000			0.00	0.00	0.00

Figure 3-43 Voltage Harmonics for Pila 15W CFL

The voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic that increases slightly from about 1.8% about 2.0% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be 2.3%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.29	114.83	1.54	0.61	0.023	77.78	-137.8 (lead)	-0.03	-0.03	0.04
2	2.27		0.73	0.29	0.000		146.3 (lag)	-0.00	0.00	0.00
3	2.23		0.97	0.39	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-44 Current Harmonics for Pila 15W CFL

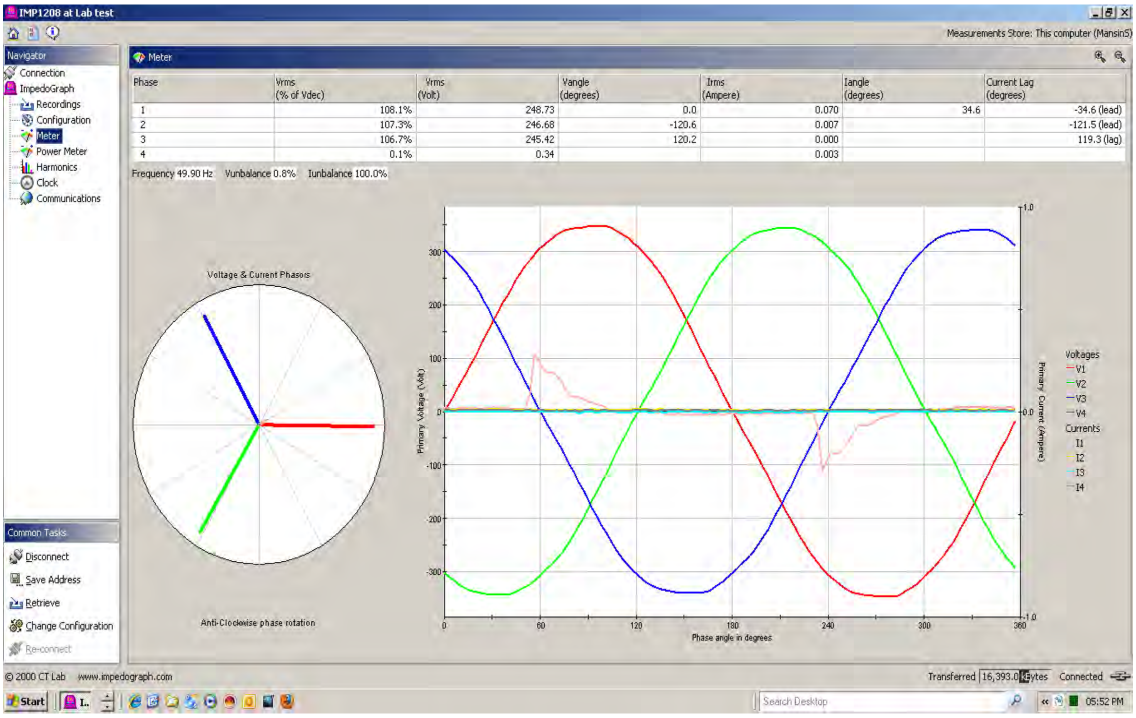
In figure 3-44 above, the current harmonics observed to be highest at the 3rd harmonic at 77.8% of the fundamental followed by the 5th which about 55.0% and above the IEC limit while rest of the harmonics are all above the minimum current harmonic limits up to the 11th harmonics. The rest on the graph from the 13th harmonic are just above 10%. The THD is observed to be at 115.1% of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic within the IEC 61000.3.2 limit of 78.2% and similarly the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within the 33 % limit while many utilities implementing large scale energy efficiency programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current by about 82%.

This lamp does not comply with the IEC61000.3.2 current harmonic limit and may pose a risk to harmonic limits on networks already close to its limit. It is therefore not recommended for use in large scale efficient lighting rollout programmes without consultation with the respective distribution network engineer responsible for QOS.

3.4.11 Laboratory Test Results : Compact Flourescent Lamp (Mr Electric, 15W)

This is a LPF 15 W CFL that is a typical domestic application replacement for a 60W incandescent (GLS. The power quality of this CFL load was observed with the Impedograph. This load is connected to the 1st phase (V1) of the 3 phase supply from the mains.



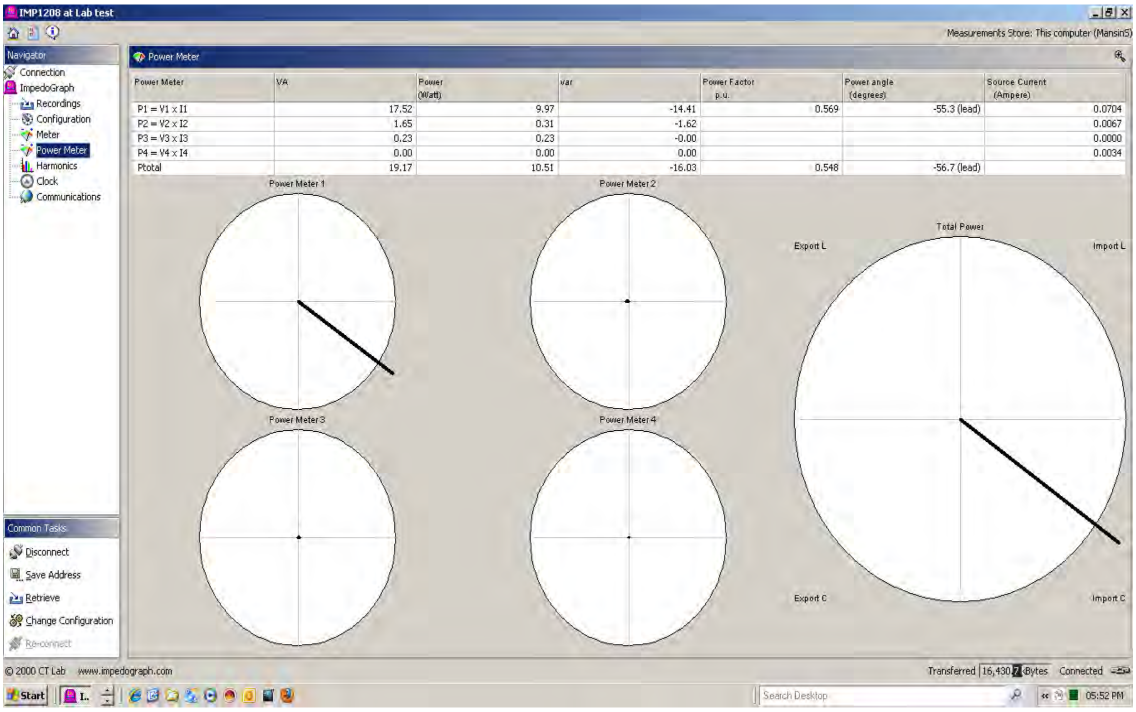
Phase	Vrms (% of Vdec)	Vrms (Volt)	Vangle (degrees)	Irms (Ampere)	Iangle (degrees)	Current Lag (degrees)
1	108.1%	248.73	0.0	0.070	34.6	-34.6 (lead)
2	107.3%	246.68	-120.6	0.007		-121.5 (lead)
3	106.7%	245.42	120.2	0.000		119.3 (lag)
4	0.1%	0.34		0.003		

Frequency 49.90 Hz Vunbalance 0.8% Iunbalance 100.0%

Figure 3-45 Voltage and Current Waveforms for Mr Electric 15W CFL

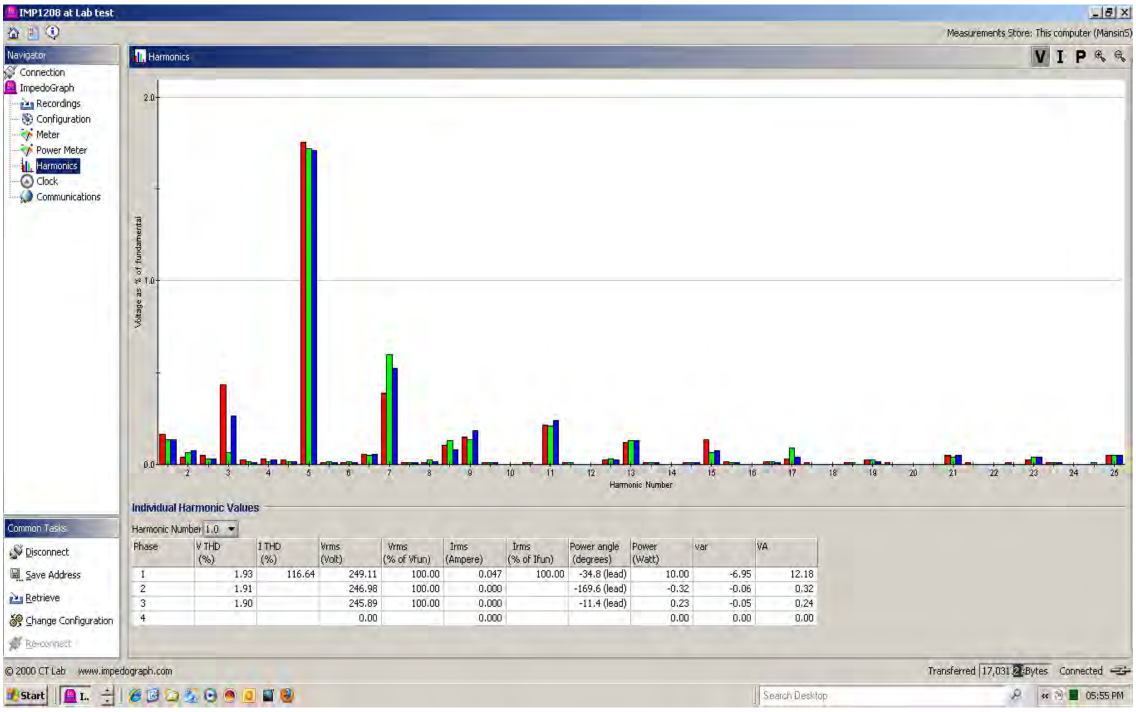
In figure 3-45 above, it is expected that I1 to be a distorted wave form as a result of being a non-linear device. I1 commences flow just before 48º, peaking just after 48º and stops flowing at zero crossing at about 100º. There is minimum load connected to the 2nd phase of the mains and no load to the 3rd phase of the mains supply hence no current flow observed.

The figure below shows that the load measured has a standard power factor of 0.569 as expected. The power factor is leading hence the load is capacitive as compared to previous older CFL designs that were inductive in nature. This should assist in improving power factor of typical networks with poor lagging inductive loads.



Power Meter	VA	Power (Watt)	var	Power Factor p.u.	Power angle (degrees)	Source Current (Ampere)
P1 = V1 x I1	17.52	9.97	-14.41	0.569	-55.3 (lead)	0.0704
P2 = V2 x I2	1.65	0.31	-1.62			0.0067
P3 = V3 x I3	0.23	0.23	-0.00			0.0000
P4 = V4 x I4	0.00	0.00	0.00			0.0034
Ptotal	19.17	10.51	-16.03	0.548	-56.7 (lead)	

Figure 3-46 Power Meter Readings for Mr Electric 15W CFL



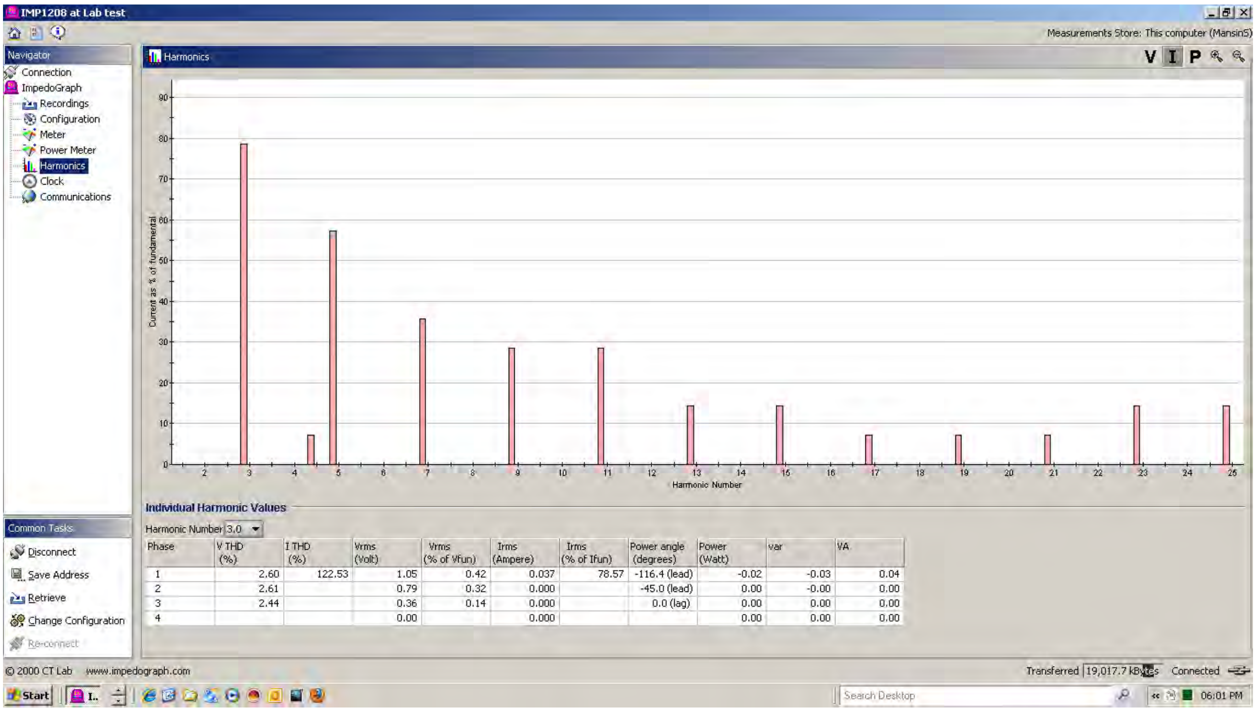
Individual Harmonic Values

Harmonic Number 1.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	1.93	116.64	249.11	100.00	0.047	100.00	-34.8 (lead)	10.00	-6.95	12.18
2	1.91		246.98	100.00	0.000		-169.6 (lead)	-0.32	-0.06	0.32
3	1.90		245.89	100.00	0.000		-11.4 (lead)	0.23	-0.05	0.24
4			0.00		0.000			0.00	0.00	0.00

Figure 3-47 Voltage Harmonics for Mr Electric 15W CFL

In figure 3-47 above, the voltage harmonic spectrum observed is very similar to the main supply without loading i.e. it has a very noticeable 5th harmonic that remains about 1.8% of the fundamental that is followed by a 7th and 3rd harmonic just above 0.5% of the fundamental. The second phase (V2) of the main supply has the impedograph and laptop connected has shown a marginal drop in harmonic level which indicates that the CFL's 3rd harmonic is out of phase with the laptop and impedograph's 3rd harmonic. The THD for the voltage is observed to be just under 2.0%.



Individual Harmonic Values

Harmonic Number 3.0

Phase	V THD (%)	I THD (%)	Vrms (Volt)	Vrms (% of Vfun)	Irms (Ampere)	Irms (% of Ifun)	Power angle (degrees)	Power (Watt)	var	VA
1	2.60	122.53	1.05	0.42	0.037	78.57	-116.4 (lead)	-0.02	-0.03	0.04
2	2.61		0.79	0.32	0.000		-45.0 (lead)	0.00	-0.00	0.00
3	2.44		0.36	0.14	0.000		0.0 (lag)	0.00	0.00	0.00
4			0.00		0.000			0.00	0.00	0.00

Figure 3-48 Current Harmonics for Mr Electric 15W CFL

In figure 3-48 above, the current harmonics observed to be highest at the 3rd harmonic at 78.6% of the fundamental followed by the 5th which about 58.0% and just above the IEC limit while rest of the harmonics are above the minimum current harmonic limits up to the 15th harmonic. The rest on the graph from the 17th harmonic are below 10.0% except for the 23th and 25th harmonic being about 15.0%. The THD is observed to be at 116.6% of the fundamental current.

The current harmonic spectrum observed the 3rd harmonic to be almost close to the IEC 61000-3-2 current harmonic limit of 78.2% and similarly the rest of the harmonics are outside of the IEC limits. The IEC expects THD to be within the 33 % limit while many utilities implementing large scale Energy Efficiency programmes expects these lamps to be within 20% and this means that this lamp also failed the IEC THD limit for current harmonics by about 83%.

This lamp is not compliant to the IEC 61000-3-2 current harmonic limitations and may pose possible risks to harmonic limits on networks already close to its limit. It is therefore not recommended for use in large scale efficient lighting rollout programmes without consultation with the respective distribution network engineer responsible for QOS.

3.5 Batch Test 1 : Results & Analysis

3.5.1 Batch 1 Laboratory Test Results : THDi (Current)

From the table 3-4 and figure 3-49 below, it is evident that all CFLs exceeded the total harmonic distortion (THD) limits although the HPF (High Power Factor) CFL was closest to the IEC 61000-3-2 THDi limits (< 33%) with a THDi of 46%. The rest of the LPF (Low Power Factor) CFLs were significantly out of the IEC 61000.3.2 THDi limits as they ranged between 105% to 122%. Although procured at a premium up to 25%, HPF CFLs remain the more suited for large scale efficient lighting rollouts. The LPF CFLs may pose a risk to harmonic levels on networks that are already close the applicable limits and may require further consultation with the respective power quality engineers for the specific network.

Table 3-4 Summary of Test Results : Current Harmonics (THDi)

No.	Lamp Load	I THD (%)
1	Radiant, 45W HPF CFL	46.7%
2	Eurolux, 20W LPF CFL	121.1%
3	LeeLite, 15W LPF CFL	116.9%
4	Megaman, 15W LPF CFL	106.4%
5	Megaman, 9W LPF CFL	108.7%
6	Philips Genie, 14W LPFCFL	106.4%
7	Eskom NFS, 14W LPF CFL	105.3%
8	Pila, 15W LPF CFL	115.1%
9	Mr Electric, 15W LPF CFL	116.6%
	IEC 61000.3.2 THD Limit	**33.0%**

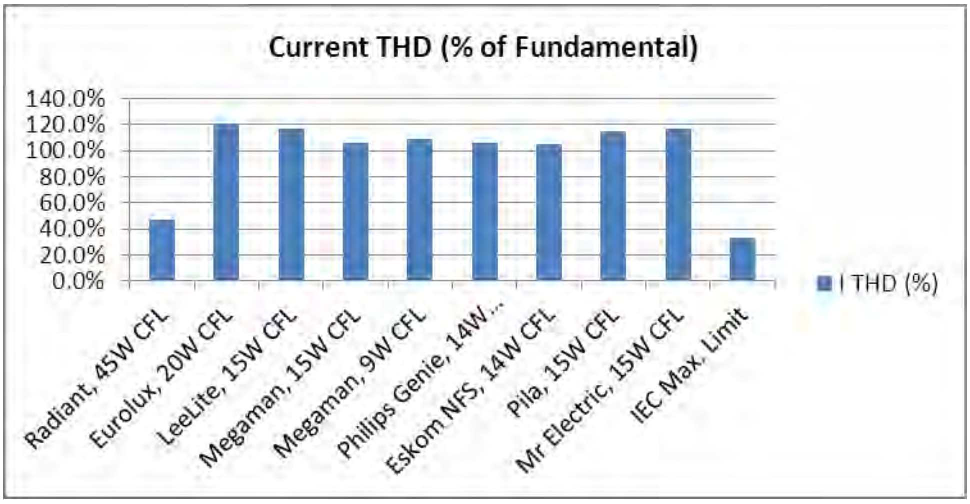


Figure 3-49 Summary of Test Results : Current Harmonics (THDi)

3.5.2 Summary of Batch 1 Lab Test Results : Low Frequency Harmonics(mA/W)

From table 3-5, figure 3-50 and figure 3.51 below, it is evident that all the lamps exceeded the harmonic limits except for the HPF CFL that complied with the IEC61000.3.2 lower frequency harmonic limits (mA/W) except for the 9th harmonic being very close to the 0.50mA/W limit at 0.56mA/W. All of the LPF CFLs did not meet the harmonic limits of the IEC 61000.3.2 limits (mA/W). This make the HPF CFLs most suitable for large scale efficient lighting rollouts. The LPF CFLs may pose a risk to harmonic levels on networks already close the IEC limit and may require further consultation with the respective power quality engineer for that specific network.

Table 3-5 Summary of Test Results : Current Harmonics (mA/W)

No.	Lamp Load	I3 (mA/W)	I5 (mA/W)	I7 (mA/W)	I9 (mA/W)
1	Radiant, 45W CFL	0.95	0.60	0.64	0.56
2	Eurolux, 20W CFL	5.34	3.32	2.40	1.92
3	LeeLite, 15W CFL	5.17	3.45	2.07	1.74
4	Megaman, 15W CFL	4.98	2.93	2.05	1.76
5	Megaman, 9W CFL	4.98	3.32	2.21	1.66
6	Philips Genie, 14W CFL	5.05	3.15	2.23	1.87
7	Eskom NFS, 14W CFL	4.95	3.30	1.97	1.97
8	Pila, 15W CFL	5.03	3.59	2.15	1.43
9	Mr Electric, 15W CFL	5.52	4.07	2.51	1.96
	IEC Max. Limit	3.40	1.90	1.00	0.50

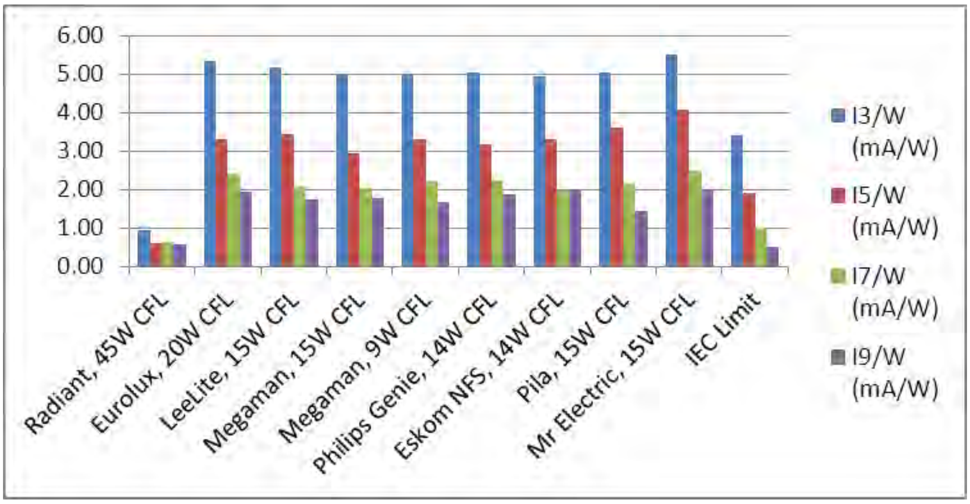


Figure 3-50 Summary of Test Result : Current Harmonics (mA/W)

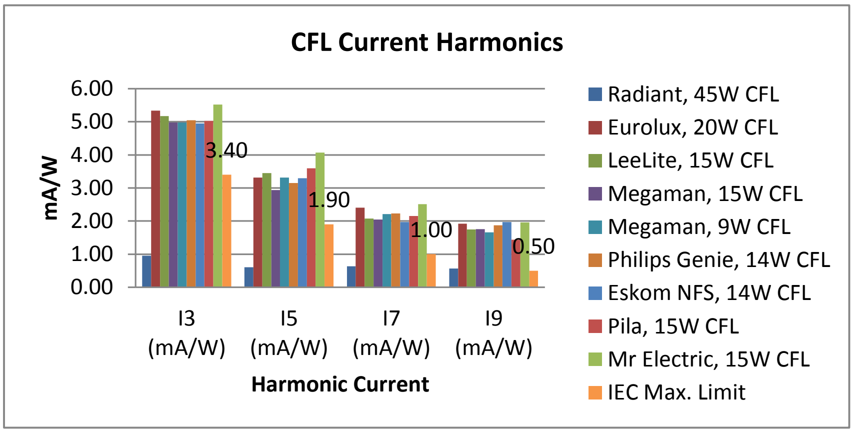


Figure 3-51 Summary Test Results : Current Harmonics

3.5.3 Batch 1 Test Results : Low Frequency Harmonics (Current as % of fundamental)

From the table 3-6 and figure 3-50 and figure 3.51 below, it is evident that all the lamps contribute significantly to low frequency harmonics (i.t.o. % of fundamental). The HPF CFL has shown to be well within the IEC61000.3.2 limits (% of fundamental) for all the lower frequency harmonics except the 9th harmonic which was very close to the 11.5% limit at 13.4%. All the LPF CFLs failed compliance to almost all of the lower frequency current harmonic levels (% of the fundamental) prescribed with IEC 61000-3-2 except for 5 out of 8 LPF CFLs tested just within the 3rd harmonic limit. The LPF CFLs may pose a risk to harmonic levels on networks that are already close the IEC limit and may require further consultation with the respective power quality engineer for that specific network.

Table 3-6 Summary of Test Results : Current Harmonics (% of fundamental)

No.	Lamp Load	I rms	I3(%)	I5(%)	I7(%)	I9(%)
1	Radiant, 45W HPF CFL	0.188	22.6%	14.3%	15.1%	13.4%
2	Eurolux, 20W LPF CFL	0.144	79.3%	49.3%	35.7%	28.6%
3	LeeLite, 15W LPF CFL	0.097	78.9%	52.6%	31.6%	26.6%
4	Megaman, 15W LPF CFL	0.107	77.3%	45.5%	31.8%	27.3%
5	Megaman, 9W LPF CFL	0.067	75.0%	50.0%	33.3%	25.0%
6	Philips Genie, 14W LPF CFL	0.104	76.2%	47.6%	33.6%	28.3%
7	Eskom NFS, 14W LPF CFL	0.097	75.0%	50.0%	29.9%	29.8%
8	Pila, 15W LPF CFL	0.044	77.8%	55.6%	33.3%	22.2%
9	Mr Electric, 15W LPF CFL	0.070	78.6%	58.0%	35.7%	27.9%
	IEC Maximum Limit	-	**78.2%**	**43.7%**	**23.0%**	**11.5%**

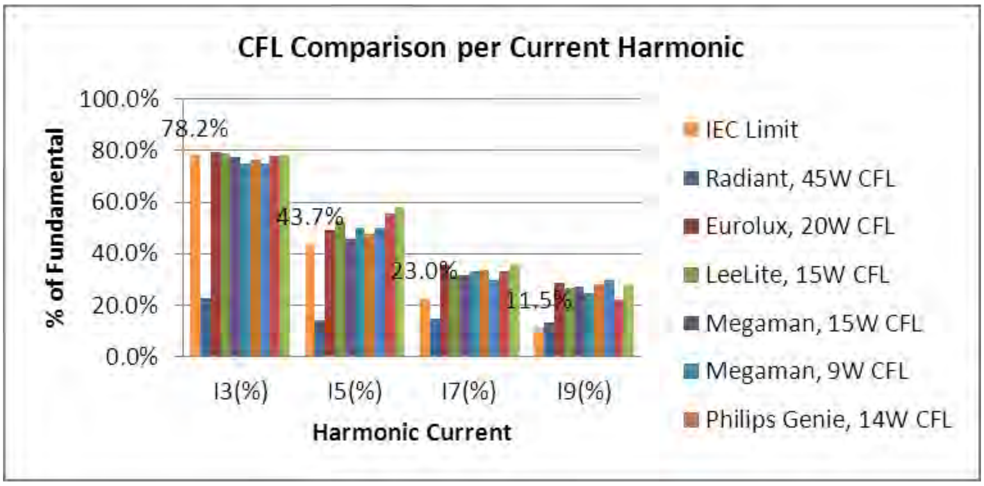


Figure 3-52 Results of Current Harmonics by CFL

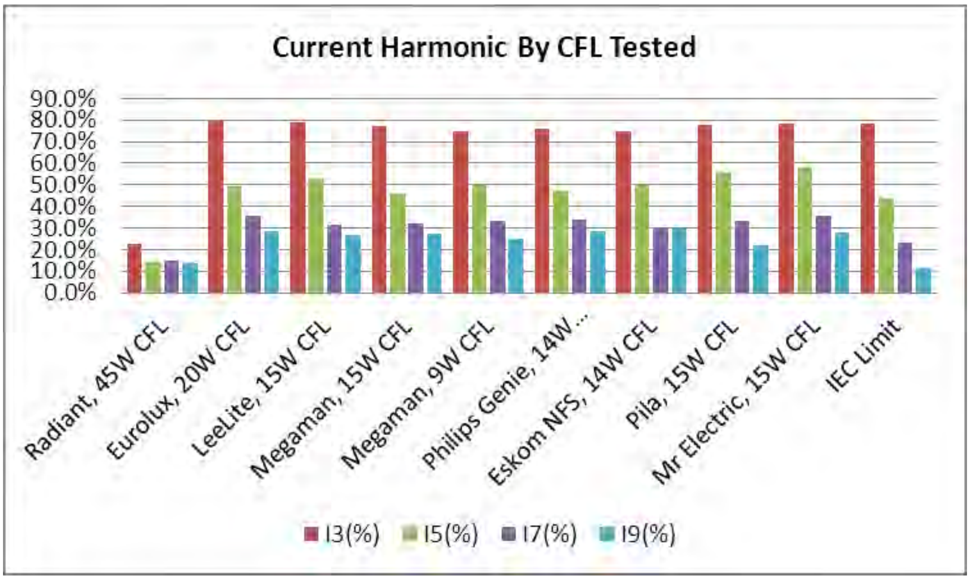


Figure 3-53 Results of Current Harmonics by CFL

3.5.4 Batch 1 Laboratory Test Results : Power Factor

From the figure 3-54 below, it is clear that all CFLs contribute to power factor and that all the lamps tested adheres to the South African standard SANS 60901/IEC 60901 with PF > 0.5 (leading) but all have however failed compliance to PF < 0.96% as prescribed in the IEC 61000.3.2. All LPF (Low Power Factor) CFLs had power factors that ranged between 0.57 to 0.62, except for the High Power Factor (HPF) lamp tested, that was measured at 0.93 which is very close to the IEC 61000.3.2 limit. All CFLs test had leading PF as compared to those original lagging PF CFLs and those tested in many of the earlier academic literature.

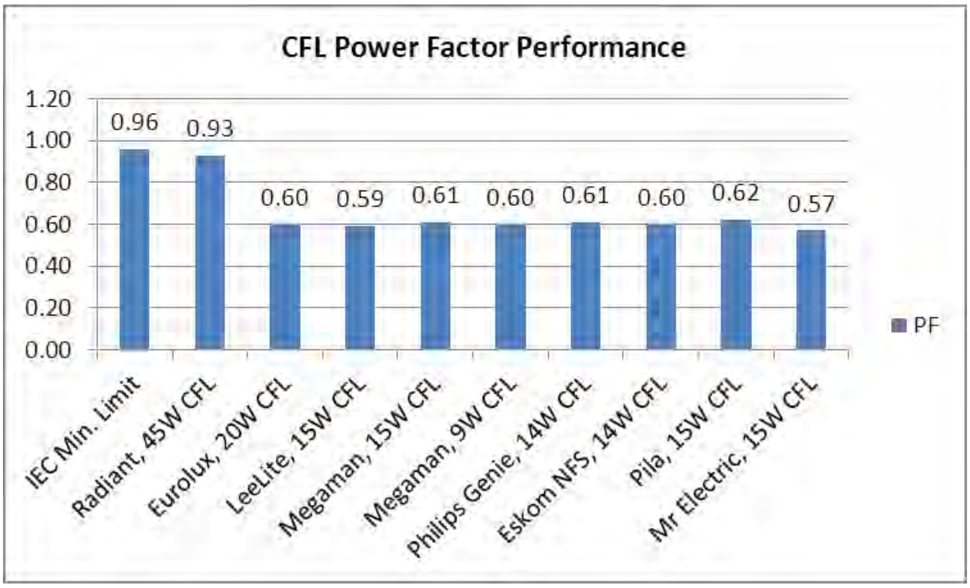


Figure 3-54 Summary of Results of Lamps Tested for Power Factor

3.5.5 Laboratory Test Results : Wattage

From the table 3-7 below, it is evident that the 2 non-premium and non-trade brands (Pila and Mr Electric) tested at the laboratory has shown to be significantly out of the printed rated wattage output. This could be a concern to consumers if the light output (illumination) does not match the replaced incandescent light output which may be mandatory in some environments.

Table 3-7 Results of CFLs Actual Wattage vs Rated Wattage @ 250V

No.	Lamp Load	Rated W	Actual W	% variance
1	Radiant, 45W CFL	45W	44.7	-0.7%
2	Eurolux, 20W CFL	20W	21.4	7.0%
3	LeeLite, 15W CFL	15W	14.8	-0.3%
4	Megaman, 15W CFL	15 W	16.6	10.7%
5	Megaman, 9W CFL	9 W	10.1	12.2%
6	Philips Genie, 14W CFL	14 W	15.7	12.1%
7	Eskom NFS, 14W CFL	14 W	14.7	5.0%
8	Pila, 15W CFL	15 W	6.8	-54.7%
9	Mr Electric, 15W CFL	15 W	10.0	-33.3%

Section Conclusion : All CFLs contribute to harmonics although the HPF CFLs have proven to be within or close to the limits prescribed by IEC 61000-3-2 for harmonics (THDi, mA/W, % of the fundamental current). This makes the HPF CFLs most suitable for large scale efficient lighting rollouts. The LPF CFLs may pose a risk to harmonic levels on networks that are already close to the prescribed harmonic limits and may require further consultation with the respective power quality engineers for that specific network.

3.6 Laboratory Batch Test 2 : CFL interactions with other loads

3.6.1 Batch Test 2 Laboratory Tests Methodology

Within the limitations of available time and access to laboratory and equipment, a second set of tests (batch test 2) as per schematic set up in figure 3-6 was conducted with the available 15x 14W CFLs.

Load Types Tested :

1. **Non Linear Load 1** **:** Phillips Genie 14W CFLs (220V- 240v 50 Hz 100mA)
2. **Non Linear Load 2** **:** HP Laptop 90W (220V-240V 50Hz 1.3A)
3. **Linear Resistive Load** **:** Osram 60W (220V-240V 50 Hz 260mA)

Test Procedure :

1. At the start of each of the test periods, each individual CFL and the interacting load/s were stabilised at mains voltage (250V) for a 60 minute period.
2. The stabilised loads at mains voltage, were then tested for 5 minutes thereby allowing for the stabilised load results to be recorded.
3. The Impedograph was utilised to conduct all power quality measurements. This recorder monitors voltage quality according IEC61000-4-30 (Class A), NRS048 (2003), EN50160, IEC61000-3-6/7 standards.
4. The Impedograph was configured to record over a 60 seconds period, the fundamental and individual harmonics for both the current drawn and voltage supplied up to the 25th order and also the standard power measurements (i.e. the real power, the active power, the apparent power and the true power factor) for the 60 seconds duration.
5. The Impedograph was wired to 3 phase mains supply in Star connection (4 wire).
6. The CFL load, the laptop load, and the GLS load were connected in parallel to the 2nd phase (V2, I2) of supply while the impedograph was connected to the 3rd phase (V3, I3) of the supply and the 1st phase (V1) had no load.

This test simulated a few typical load interactions with CFLs at laboratory supply voltage of 250V as listed below :

1. 6x 14W CFL’s alone (i.e. 100.0% of real power loading)
2. 6x 14W CFL’s (48.3%) with a 90W laptop (51.7%)
3. 6x 14W CFL’s (18.9%) and 6x 60 W Incandescent lamps (81.1%)
4. 6x 14W CFL’s (15.7%), 6x 60 W Incandescent lamps and a 90W laptop (16.8%)
5. 12x 14W CFL’s (100.0%) alone
6. 12x 14W CFL’s (65.1%) with a 90W laptop (34.9%)

7. 12x 14W CFL’s (18.9%) and 12x 60 W Incandescent lamps (81.1%)
8. 12x 14W CFL’s (17.1%), 12x 60 W Incandescent lamps and a 90W laptop (9.2%)
9. 15x 14W CFL’s (100.0%) alone.
10. 15x 14W CFL’s (70.0%) with a 90W laptop (30.0%)
11. 12x 14W CFL’s (18.9%) and 12x 60 W Incandescent lamps (81.1%)
12. 15x 14W CFL’s (17.5%) and 9x 60 W Incandescent lamps, 90W laptop (7.5%)

3.6.2 Laboratory Batch Test 2 : Results and Conclusions

The THDi results of these tests are collectively displayed in figure 3-55 on a single graph and also the THDv results of these tests are collectively displayed in figure 3-56 on a single graph.

CFL load alone : It is observed that THDi changes marginally when 6 CFLs (110.83%) increases to 12 CFLs(110.60%) but an increase of between 2.3%-2.5% observed when it is increased to 15 CFLs (113.37%). Similarly a marginal change in THDv is observed when 6 CFLs (1.42%) increased to 12 CFLs (1.41%) but an increase of 45.0%-47.1% was observed when the CFLs increased to 15 CFLs (113.37%). This implies that CFLs loads alone does not comply with IEC 61000.3.2 THDi limits of 33%.

CFL and non-linear laptop load : It is interesting to notice that there is some form of cancellation i.e. a 15.5%-16.0% reduction in CFL THDi when interacting with another non-linear device like a laptop but marginal increases (3.8%-9.9%) observed with the THDv. In this case CFLs formed 48.3% to 70.0% of the combined load and the THDi (93.09%-95.24%) although reduced it is still not within the IEC 61000.3.2 THDi limits.

CFL and linear GLS load : It is interesting to notice that there is noticeable damping of harmonics i.e. a 78.6%-79.8% reduction in CFL THDi when interacting with a linear load like a GLS bulbs but a damping of 8.1%-35.9% observed with the THDv. In this case CFLs formed 23.3% of the linear load and 18.9% of the combined load and the THDi (22.8%-23.75%) reduced to levels within the IEC 61000.3.2 THDi limits of 33%. CFLs therefore require the presence of adequate linear resistive loads to contain the harmonic disturbances within IEC THDi limits. This is also confirmed in the Field Test 1 in chapter 4.2.

CFL, non-linear laptop and linear GLS load : It is interesting to notice that there is noticeable damping of harmonics i.e. a 78.0%-79.9% reduction in CFL THDi when interacting with both linear load (like a GLS bulb) and non-linear loads (like laptop) but the damping of 1.4%-32.5% observed with the THDv. In this case the CFLs formed 15.7%-17.5% of the combined load, while the combined non-linear loads formed 25.0%-32.6% of the combined total load and 33.3%-48.3% of the linear load, resulting in a THDi (22.68%-24.36%) levels being reduced within the IEC 61000.3.2 THDi limits of 33%. Non-linear loads including CFLs therefore will require the presence of linear resistive loads to perform within IEC THDi limits.

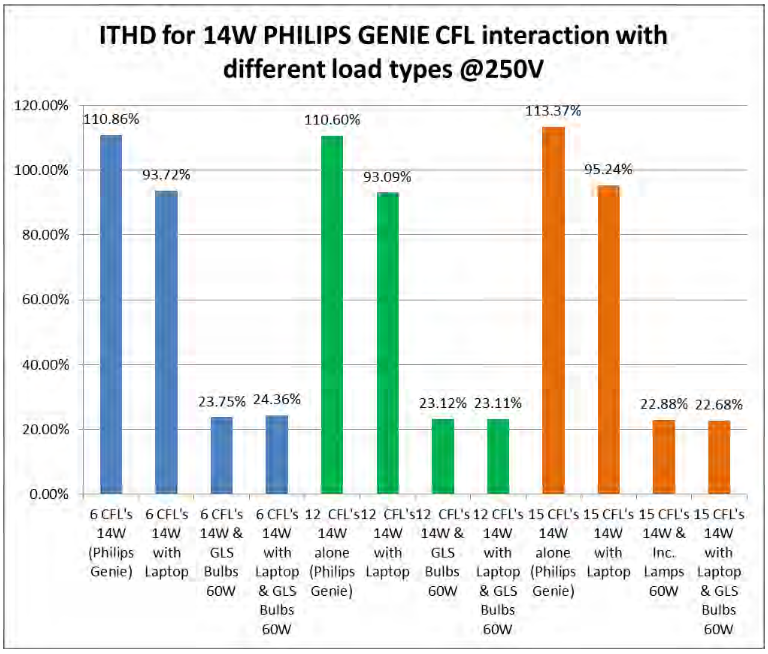


Figure 3-55 Summary of THDi Results for CFLs interaction with other loads

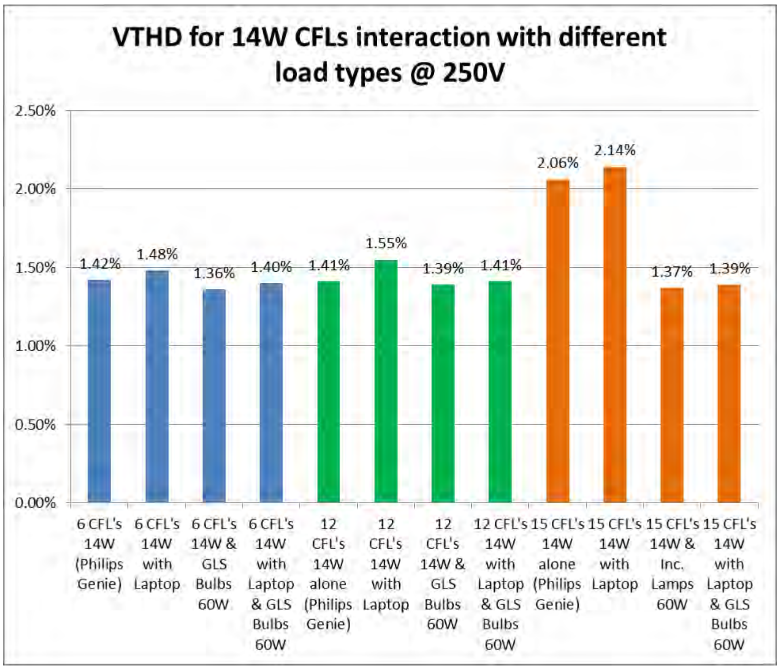


Figure 3-56 Summary of THDv Results for CFLs interaction with other loads

CHAPTER 4 : NETWORK IMPACT ANALYSIS

Now that we have established up to this point the need for energy efficiency, the role of CFLs in large scale efficiency programmes, the need for appropriate standards for good QOS on the network, the characteristic of CFLs utilised in large scale CFL programmes, it is important that we understand how these devices could impact the network power quality. This chapter will explore further the network power impact of CFLs from a global view of field experience and appropriate models.

4.1 Impact of CFL's on Network Power Factor, [1], [15]

According to [1], low power factor equipment (load) could cause a rise in both network losses and also the associated energy costs. Industry often installs power factor correction (PFC) capacitors to compensate for a grid that tends to be inductive. To satisfy IEC 61000.3.2 harmonic limits, electronic ballasts CFLs greater than 25W should have a PF of 1 and would require an active built in PFC circuit. The limitation on the power factor itself is not a direct standard requirement but rather a consequence of the required standards for harmonic current. Modern CFLs will not dominate the total grid active power demand because of their capacitive nature are less likely to have an adverse impact on the grid as they compensate the typically inductive network.

While incandescent lighting represent linear loading on a network, the electronic ballasted CFLs represent nonlinear loading. Unlike the consumer with maximum benefits in the energy bill from a large scale residential CFL programme due to efficacy (i.e. lumen/Watt) and not PF, however the utility can maximise the network savings from higher power factor CFLs. This is because higher current will be required to manage the system peak demand resulting in unnecessary network losses and this added system stress that leads to :

- infrastructure (i.e. transformer/s, cable/s and motor/s) overheating,
- capacitors accelerated aging,
- and telecommunications systems interference.

This situation can be remedied by utilising high power factor (HPF) CFLs at a premium in an attempt to limit any peak demand waste (i.e. technical losses and heating) and network infrastructure stress caused by regular LPF CFLs. HPF CFLs in essence would display PF characteristics similar to the linear incandescent loads retrofitted during large scale CFL programmes i.e. further maximising the utilities returns on energy savings from large scale CFL programmes. [1]

While HPF CFLs (PF > 0.85) are beneficial to the utilities seeking to maintain power quality within harmonic limits or additional network capacity savings, there are no direct benefits to the consumers, manufacturers and society at large. It for this reason that the European Council for Energy Efficient Economy (ECEEE) supports the European Commission's gradual approach in tightening of requirements for power factor rather than immediate hard and fast mandatory requirements. [1]

Displacement power factor formula is the relevant method for determining power factor impact of harmonic sources including CFLs on a transmission network. The introduction of PFC capacitors to the distribution system addresses the low displacement power factor as it provides the necessary compensating reactive power (kVAr) loading for inductive devices. Introducing of reactors allows the PFC capacitors to be configured as harmonic filters where required. A number of power quality-related concerns such as increase in harmonic distortion, harmonic resonance, and over-voltage transients should be considered prior to the installation of PFC capacitors. [15]

CFL PF Impact Case Study : The Auckland case study in [15], revealed that a winter evening peak residential load of 930 MW with a residential peak load of 2.3 kW per home with lighting load constituting around 11%. If 3 incandescent lights (i.e. PF = 1) per home were replaced with LPF CFLs (PF = 0.5) would reduce the household displacement power factor by 0.04 pf as compared to replacing 3 incandescent bulbs per household with HPF CFLs (Pf = 0.9) resulting in a power factor impact per household to be 0.01 pf. Increasing the power factor per home by 0.03 pf need capacitive compensation of 0.109 kVAr per kW of household load. It was established that capacitive compensation of 0.381 kVAr (i.e. $7.60 @ $20/kVAr) needed per home in compensating for the use of a LPF CFL rather than a HPF CFL. This may not be the case with modern CFLs that now has leading power factors.

CFL PF Impact Model : Considering that most papers focus on older inductive CFLs, allowed the opportunity to theoretically model the network impact of power factor alone using both LPF (i.e. 15W at PF=0.6 leading) and HPF (i.e. 15W at PF=0.96 leading) CFLs with leading power factor when retrofitting linear incandescent lighting (i.e.60W at PF=1). The first step involved in making a few assumptions which assumes a residential network with evening peak of 100 MW as a basis with a typical South African PF (i.e. PF=0.85 (lagging) in worst case scenario and PF=0.95(lagging) as the best case scenario). Like in the Auckland case earlier, a typical 11% lighting load (i.e. 11 MW) is assumed. The load comparison of 11MW of network incandescent lighting (IL) load to energy efficient CFL load at 2.75 MW is shown on the table 4-1 to understand the loading impact on a 100 MW network.

Table 4-1 Load Impact of Retrofitting 11 MW Incandescent Lighting with CFLs

	Incandescent Load (PF=1)	Impact of LPF CFL (PF = 0.6) after IL retrofit	Impact of LPF CFL (PF = 0.96) after IL retrofit	Impact Difference (LPF vs HPF)
MW	11.0	(2.75-11.0) = -8.25	(2.75-11.0) = -8.25	**(8.25-8.25) = 0**
MVA	11.0	(4.583-11.0) = -6.42	(2.864-11.0) = -8.14	**(-6.42+8.14) = 1.72**
MVAr	0	(3.63-0) = 3.63 (lead)	(0-0.80) = 0.80 (lead)	**(3.63-0.8)=2.84 (lead)**

The table 4-1 highlights that there is no additional benefit to the real power drawn when retrofitting incandescent lighting with HPF CFLs instead of LPF CFLs. However the LPF CFL provides 2.84 MVAr's (leading) more than the HPF CFL that could be beneficial to an inductive loaded network. This loading is then modelled onto a 100 MW network with 2 scenarios for network power factors and the impact is shown on the table 4-2 below.

Table 4-2 Network Impact of Retrofitting Incandescent Lighting with CFLs

	100 MW Network @ PF = 0.85 (lagging)				**100 MW Network @ PF = 0.95 (lagging)**			
	Before	**Impact After CFL Retrofit**			**Before**	**Impact After CFL Retrofit**		
Lighting Load	**60 W IL**	**15 W LPF CFL**	**15 W HPF CFL**	**Impact Difference**	**60 W IL**	**15 W LPF CFL**	**15 W HPF CFL**	**Impact Difference**
MW	100.0	100.0-8.25	100-8.25	**0**	100.0	100.0-8.25	100.0-8.25	**0**
MVA	117.6	117.6-6.42	117.6-8.14	**1.72**	105.3	105.3-6.42	105.3-8.14	**1.72**
MVAr	61.9 (lag)	61.9-3.63	61.9-0.80	**2.84 (lead)**	32.9 (lag)	32.9-3.63	32.9-0.80	**2.84 (lead)**
PF	0.850 (lag)	0.825 (lag)	0.838 (lag)	**0.013 (lag)**	0.950 (lag)	0.928 (lag)	0.944 (lag)	**0.016 (lag)**

The table 4-2 highlights that there is no additional benefit to the real power (0MW) drawn when retrofitting incandescent lighting with HPF instead of LPF CFLs. On a network with a lagging 0.85 PF, the leading LPF CFLs can make a more favourable impact on the network's PF by 0.013 (PF) when compared to the HPF CFLs, however this leading LPF CFLs make a more favourable impact on the 0.95 lagging power factor network by 0.016 (PF) when compared to the HPF CFLs.

It is noted that for a lagging PF network, the LPF CFLs leading PF provides more PF compensation benefit than a HPF CFL. This LPF CFL leading PF compensation will have maximum benefit when the network reactive lagging load is equal to the LPF CFL leading reactive load. In this theoretical example the network lagging reactive load will be 3.63 when the network power factor approaches 0.9993 lagging PF. At a network power factor 0.9993 (lagging) the LPF CFL is able to provide 100% PFC compensation.

Section Conclusion : While there is movement towards tightening of power factor requirements for CFLs, the additional benefit remains for the utility and the electricity distributor. While earlier papers publishes the negative impact of inductive CFLs on networks, Table 4-2 above highlights the positive impact of modern leading power factor CFLs on a network. This model also highlights the benefits of leading PF CFLs on a typical inductive network. The maximum apparent and reactive power compensation is realised from the LPF CFLs. The maximum theoretical reactive power compensation benefit is achieved when network lagging reactive load equals the leading LPF CFLs leading reactive power.

4.2 Impact of CFL's on Network Harmonic Distortion, [1], [37], [38], [28], [39], [14]

According to [1], it is noted that network harmonic pollution in typical households are from non-linear appliances like personal computers, televisions and electronic ballasted lighting. In addition to load reduction from replacing of conventional incandescent lighting (IL) with non-linear CFLs is the unfortunate consequences of harmonics. Harmonics emissions distort the mains voltage waveform resulting in losses increasing at the generators and the distribution network leading to an overloaded 3 phase star distribution network's protective earth neutral. Energy suppliers recommend that CFL manufacturers introduce integrated electronic compensation for the lower harmonics produced.

The IEC standard 61000-3-2 limits provide a control measure for negative effects from CFL harmonic current emissions. The electronic lighting equipment with an active power > 25W are subjected to stringent harmonic limitations by the standard while harmonic emission reductions for appliances rated < 25 W are excluded from mandatory regulation requiring compensation. The Community of the Austrian Electricity Suppliers conducted detailed laboratory and field measurements to prove that the large scale use of CFLs were not detrimental to the supply voltage quality. These results indicated that no further supply quality improvement remedies are required. This was also in alignment with the investigation conducted by German umbrella organisation (ASEW) representing 6 of their local suppliers of energy that also did not experience any quality issues from large scale CFL deployment. Although it is further stated the IEC 61000-3-2- requirements sufficiently safe guards the supply quality. [1]

Field Test 1 : According to [37], measurement based field tests were conducted to investigate the difference in harmonic impact between ILs and CFLs. The before metering results versus the after were recorded for the ILs that were exchanged for CFLs. The metering of the residential complex was conducted on the main supply feeder for all three phases. The results indicated a noticeable difference in the harmonic distortion levels for each individual harmonic as well as the total harmonic distortion (THD). It was concluded that the harmonic distortion levels resulting from CFLs on the main supply feeder is a concern. The advantage of CFLs are that it reduces the power consumption per dwelling from the lighting load but there is a clear indication that CFLs inject harmonics and cause distortion even when they are used in combination with ILs. ILs are linear loads and are known to absorb harmonics or put another way, ILs dampen harmonics. Therefore, the harmonic impact of CFLs must be considered in an attempt to reduce the harmonic emissions into electrical networks. Another important observation is that lighting loads should be equally distributed between the 3 phases to ensure that the distortion levels are also equally distributed between the 3 phases.

Simulation Model 1 : In [38], the harmonic characteristics for typical commercially available CFLs were presented. The paper also analyses and predicts the possible impacts that CFLs have on harmonic levels on a distribution system. This study highlights that large scale CFL's can result in harmonic problems for a distribution feeder. The simulation results obtained highlighted that the distortion level expected depends on the type of CFL used and the distribution parameter. The current distortion for the CFLs are very high, that even when CFLs are 10% of the total load, results in voltage distortion shown to be unacceptable at point of common coupling. The deployment of higher distortion current LPF CFLs should be restricted in favour of lower distortion current HPF CFLs that are now commercially available. This paper recommends further research to be conducted on different distribution network scenarios (i.e. industrial, embedded generation, weak voltage) to determine tolerance limits for maximum CFL penetration.

Simulation Model 2 : According to [28], Australia's announcement to phase out of ILs in favour of CFLs by 2010, resulted in a promotional programme intended to provide one million free CFLs to their residential customers. Prior to this large scale incandescent replacement programme were concerns about the possible negative impact on the network arising from harmonics and low power factor of CFLs. A harmonic load flow simulation software model of the distribution network supplying the residential load was constructed with consideration for :

- the behaviour of transformers and conductors at frequencies of harmonics,
- the spatial spread of customer loadings,
- and the effects of CFLs on network parameters (i.e. thermal loading, flow of power, voltages at steady-state, and voltage THD).

The simulation revealed that the replacing of ILs with CFLs will in addition to reducing the current flow in the distribution network, but also the peak power demand and apparent power in both low and medium voltage feeders and also improve feeder voltage regulation and unfortunately increase the level of harmonic voltage distortion. While replacing a single IL with a CFL in each of the one million households as proposed did not increase the voltage distortion significantly. Replacing all ILs with LPF CFLs raised concerns w.r.t. voltage distortion reaching unacceptable limits depending on the existing level of network voltage harmonics. While large scale replacement from ILs to LPF CFLs may increase voltage distortion outside the limit if the network is already close to the 5% harmonic limit however LPF CFLs by itself may not be enough to result in network voltage distortion exceeding regulatory limits of 5%.

Although the proposed program proceeded, all future large scale CFL programmes are to proceed with caution. Consideration should be given to mitigation measures for all household non-linear equipment that significantly contribute to harmonic distortion and this include personal computers, televisions and newer white goods appliances that utilise variable-speed drives like air conditioners. Household scale embedded generation provides harmonic mitigation opportunity as it reduces the harmonic currents network propagation distance.

Simulation Model 3 : In [39] a model was developed to assess the impact of CFLs on South Island 220 kV power system. The power system is made up of a 300 kVA transformer, 8 x 70 mm^2 LV feeders, each with 8 x service mains feeding 64 customers (i.e. 4.7 kVA after diversity maximum demand per customer (ADMD)). The model is typical of a generic LV power system making it possible to scale the results from this study to similar systems with some caution. The study models the THD controlled largely by the distribution transformer impedance which is 5% on a 300 kVA base for this case. This study determines maximum penetration load of 920 x 20 W lamps, or about 14 lamps per household is required for the prescribed 5% harmonics limit to be reached at the customer's main switch. A cautious approach is warranted with model as other sources of harmonic distortion needs to be considered in addition to the THD caused by increase of non-linear lamps.

This model has also been scaled to assess the CFL loads required before reaching the expected THD levels for other ADMDs and sizes of transformer. A scaled model considered a 200 kVA transformer with 4.5% impedance and 43 customers assessed accommodating approximately 450 lamps(i.e. 10 lamps per customer), prior to THD reaching 5%. Another scaled model considered networks with low ADMD with more customers per transformer assessed to accommodate proportionately less number of lamps per customer. Similarly in a third scaled model for a 200 kVA, 4.5% transformer impedance, 3KVA ADMD and 67 customers, assessed to accommodate up to 6.7 lamps per customer. The model was tested for use of a higher performance CFL lamps that comply to the proposed Australian Standard AS3134 and it revealed that the network will be able to accommodate more lamps (i.e. approximately 2500 lamps representing 39 lamps or 750Watts per household) before reaching the 5% THD limit on the network.

Simulation Model 4 : This paper [14] researches the issues relating to voltage harmonic distortion from large scale CFL deployment on a LV system. The model adopted the current harmonic spectrum characteristic of CFLs under various supply conditions as established from another research. A typical LV electrical installation of a hotel was analysed using this data together with valid international standards. This analysis revealed that the CFLs total active power need to be limited to 10% of the rated transformer power in order for the voltage THD to remain within IEC/TR3 61000-3-6 limits at the busbar supplying other appliances. This limitation is valid when designing lighting for a similar type of commercial building. More CFLs can be accommodated either by deploying harmonic filters at transformer or by deploying IEC 61000-3-2 compliant HPF CFLs. This model could also be easily applied to residential customers.

Simulation Model 5 : This research [19] assesses the level of THD introduced by large-scale IL to CFL retrofit in weak LV networks. This research utilised harmonic content field measurements and other data measurement sources for the island of Arki electrical network characteristics considering that it is receiving supply by the photovoltaic (PV) station in order assess if the THD at all buses are within 5% with the addition of more CFLs. This is relevant to South Africa considering the recent introduction of Independent Power Producers (IPPs) bringing a new set of challenges to the network like the autonomous PV station, which supplies the island also generates harmonics just like CFLs. The simulation of harmonic flow within the entire network and CFLs showed the impact on quality of power. The following results derived from the simulation are crucial and must be considered when designing networks for weak PV systems :

- Power quality within weak PV networks will be sensitive to non-linear loads like large scale IL to CFL programmes as the use of CFLs for energy efficiency such networks may result in unacceptable network voltage distortions greater than 5%,
- Large scale incandescent replacement to CFLs in excess of 30% may result in unacceptable network voltage THD greater than 5% and possibly worse if other non-linear loads are considered,
- To manage the line voltage THD within acceptable limits on weak voltage systems require appropriate consumer load regulation i.e. regulating the types of electrical equipment (load quality) and their load quantity.

Section Conclusion : The introduction of non-linear equipment on the network induces harmonic current flow. The replacement of ILs with energy efficient lamps results in a desired reduction of network load however it also inject harmonics which may result in an overloading of the protective earth neutral conductor in a 3 phase (star) network. CFLs by nature of the electronic ballast induce low harmonic interference and utilities should influence lighting manufacturers to introduce electronic compensation in CFLs as prescribed by IEC standard 61000.3.2 harmonic limits. These studies discussed indicate that the voltage THD is mostly determined by the distribution transformer’s impedance. Studies have also highlighted that the CFLs total active power be limited to 10% of the rated transformer power in the case of commercial building to contain the voltage THD on the busbars to be within the IEC/TR3 61000-3-6 limits. Special precaution need to be taken when applying CFLs to network with weak voltage or supplied by photovoltaic (PV) system especially now with the introduction of Independent Power Producers (IPPs) with renewable energy sources like PV and wind power.

CHAPTER 5 : GUIDELINE FOR UTILITY ENGINEERS

5.1 Ensure Network Compliant CFLs [41]

This chapter provides some guidelines to utility engineers faced with the need to better understand the impact of large-scale CFL deployment as a demand-side intervention. According to [41], *"although the arithmetic sum of harmonic currents generated at LV by several million CFL's are significant, the actual impact on the system voltage seems to be less significant than would be expected. Several factors contribute to this, i.e.: reduced 5th harmonic emission under non-sinusoidal conditions, the cancellation effect of LV power supply harmonics and CFL harmonics, damping at LV. This is even in the case of low-economic areas in developing countries. Concerns around the impact of harmonics need not hamper the large-scale roll out of CFLs as required under the emergency conditions in South Africa. The test conditions for IEC 61000-3-2 compliance require a sinusoidal voltage source and it should be noted that "actual" voltages at LV may already be distorted, resulting in sometimes higher, and sometimes lower current emissions."* It is important that CFLs are compliant to IEC61000.3.2 w.r.t harmonic limits and PF to minimise the possible impact from large scale roll out programmes on networks close to voltage THD limits of 5% as per IEEE 519-1992 standard.

5.2 Network Engineers Role in Large Scale CFL Rollout Programmes

Considering the high volume of CFLs entering the market, there needs to be tighter control on the power quality standard of CFLs. Existing international lighting industry CFL standards need to be thoroughly reviewed and adopted by utilities were applicable. Lighting industry standards authorities need to ensure that we reduce the possible adverse impact on power quality by controlling the import of sub-standard quality from entering the market. Chapter 2.5.4 clearly highlights the current development and most importantly the gaps with the existing CFL standards as there is no attention to harmonics especially w.r.t. compliance to the limits prescribed in IEC61000-3-2. Given the nature of the CFLs i.t.o. harmonics and power factor, it important for the utility's power quality engineers to have an understanding to be able to have a more pro-active role and influence on large scale efficient lighting rollout programmes especially on networks already nearing the harmonic limits. This implies that the utility power quality engineers responsible for quality of supply on the respective distribution network should request for CFL compliance to the IEC61000-3-2 requirements as a minimum in conjunction with the existing South African or international CFL standards or revise existing network design standards to accommodate large non-linear loads that will also extend the system lifespan.

5.3 Modelling Higher Voltage Harmonics [14]

Impedance network modelling is important in calculating voltage harmonic components. Equivalent serial impedances are utilised to model all network conductor/s and transformer/s. Capacitors are modelled as capacitance between the busbars nodes and reference potential nodes, similarly other load types (i.e. resistive, induction motors, etc.) will also be modelled as impedances between the loads connection node and reference potential nodes. When capacitors don't exist, the influence of impedance for loads are negligible and could be excluded from the impedance network model. Nonlinear loads like CFLs are often modelled using harmonic current sources and each harmonic impedance is modelled separately.

The model for transformers and conductors are established utilising impedance with a constant inductance (*L)* and constant resistance (*R)* and whereby for the *v*th harmonic they are represented with impedance as per formula below (i.e. in this case $f = 50$ Hz) :

$$\boxed{\boldsymbol{Z = R + \mathrm{j}v\omega L = R + \mathrm{j}2\pi v f L}}$$

It should be noted that harmonics in the order of $v = 5, 7, 11, 13, 17, 19$ provide direct sequence impedance values for R and L while zero sequence impedance are for those harmonics of order $v = 3, 9, 15$, etcetera. Consideration for the skin effect is required for higher degree of accuracy.

When it is assumed that the current harmonic spectrum is not influenced by distorted voltage then the modelling of nonlinear loads like CFLs is with an ideal current source. However where there is a considerably greater harmonics anticipated in the supply, the model should be enhanced to include impedance in parallel to an ideal current source. The application of such models are applied in the next section. [14]

5.4 Managing Maximum Penetration of CFLs, [14], [40]

The following cases studies provide guidance in managing the maximum CFL penetration into a power system in an attempt to manage the network harmonic distortion in different scenarios :-

Case 1 : According to [14], it discusses how to manage the voltage THD on the busbars within the harmonic limits of IEC/TR3 61000-3-6 simply by ensuring that the total active power of large scale deployment of CFLs to be within 10% of the transformers power rating when designing the entire lighting in a typical commercial building which in this case is a hotel. This recommended limit of 10% is based on the scenario of no further current harmonic filtration of higher current harmonics. Harmonic filtration at the substation allows for a marginal increase of CFL load beyond 10%. Therefore in cases where a higher total power of CFLs is sought, then either application of network current harmonic filtration or HPF CFLs could assist. This voltage harmonic influence from CFLs in a commercial building can be easily applied to residential customers.

Case 2 : A New Zealand study, [32], assessing the maximum volume of CFLs allowed per household to remain within the network 5% voltage limit. The model represented the South Island 220 kV network starting at the busbar to the customer distribution board (i.e. PCC (point of common coupling)). This study revealed that the voltage THD at the distribution board achieved 5.0% from a loading of 920 x 20 Watts CFLs (i.e. 14 lamps per home). This assessment also revealed that the impedance of the transformer (Trfr) is most responsible for the voltage THD at the PCC. It should be noted that lower after diversity maximum demand (ADMD) on a network means more customers per transformer resulting in fewer CFLs per customer to meet and exceed the network 5% voltage THD limit. This model is with practical reason scaled to 3 other network scenarios as illustrated on the table 5-1 below.

Table 5-1 Summary of Maximum CFL Penetration Model Results,

Trfr Size (kVA)	Trfr Impedance (%)	THD(V) Limit (%)	Customer ADMD (kVA)	Maximum Customers / Trfr	Max CFL Load / Trfr (kVA) & % of Trfr Load	Max CFLs (20W) / Customer
300	5.0	5.0	4.7	64	18.4 (6.1%)	14
300	5.0	8.0	4.7	64	50.0 (16.6%)	39
200	4.5	5.0	4.7	43	9.0 (4.5%)	10
200	4.5	5.0	3.0	67	8.9 (4.5%)	6.7

Case 3 : In this 1992 case, [32], Lincoln University (LU) was considering retrofitting 2500 CFLs on their premises. They conducted an experiment to determine how the harmonic penetration of this CFL deployment impacted the distribution system by ignoring interaction with any other source of harmonics. The test results highlighted that :

- The university should use much less than the proposed 2500 LPF CFLs as it would violate the applicable standard in New Zealand (i.e. AS/NZS 61000-3-2 : 2003).
- The university could have been outside the equivalent European standards harmonic limits (i.e. THD and the higher harmonic limitations). The European standards offer greater leniency when compared to the New Zealand standard on total harmonic

distortion (i.e. <8% in Europe) and also lower order harmonics although stricter than New Zealand's limits for higher order harmonics.

- If HPF compact fluorescent lamps meet AS-3134 (Australian Standards preceded AS/NZS 61000:3:2) were used then the network voltage THD would be within limits.

Case 4 : In this documented case, [15], a road lighting scheme was designed for a total of 1 MW of lighting load, powered from a 1 MVA transformer source. Despite the lamps already meeting the EN 61000-3-2 limitations, the harmonic currents measured raised concerns that the lamps used were limited to 70% of their rated power to prevent excessive heating in the transformer. Although the cause of this has not been investigated further, it can also easily be a case of either the network was already at its voltage THD limit or the transformers 1000kVA apparent power loading may be exceeded by the apparent power of the 1000 KW CFL load at a lower PF.

Case 5 : In [15], Sweden's Lund University Hospital decided against the consideration for use of CFLs after realising their huge quantities of non-linear electrical appliances on campus. To also add a large scale CFL deployment would have increased the THD at the university building. It is also possible that when many types of electronic appliances on same network could also result in a positive impact on quality of power i.e. such loads draw high levels of harmonic current could be out of phase resulting in a reduction of harmonic voltages as experienced at the customers.

The impact made by harmonics on a power system is largely influenced by the characteristics of the power system is crucial consideration. Unlike the American system, the New Zealand system has a radial system with a higher source impedance which becomes prone to issues from the third harmonic. The European delta-star transformer/s inherently create an enclosed path harmonic currents within the delta winding, thus providing harmonic isolation between the transformer secondary and primary. Mass deployment of LPF CFLs may adversely increase the third harmonic pollution of a radial system. Rural distribution systems will also differ significantly compared to urban system because of a higher loading level and the capacitive effect with urban underground cables.

5.5 Managing Impact of Harmonics, [35], [14]

The role of the Utility Engineers is to ensure that the network has good power quality and this includes playing a pro-active in the large scale efficient lighting programmes. The flow diagram below highlights their role in the sub-process of managing the utilities assets within their life-cycle.

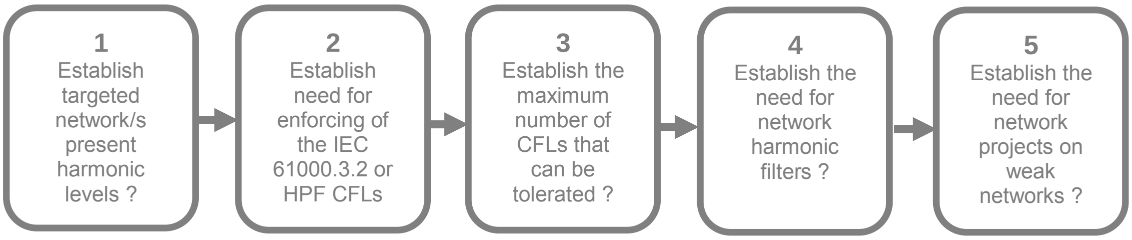


Figure 5-1 Role of Utility Power Quality Engineer in Large Scale CFL Programmes

Prior to a large scale CFL programme, once the utility's power quality engineer establish that network is not well within the harmonic limit (THD<5%) then he/she needs to influence the type of CFLs (IEC61000.3 2 compliant or HPF CFLs) and/or the volume limitations to manage network harmonic limits. If this is not possible then the two simple solutions to manage harmonic system issues are. :

- strengthening (reinforcing) of power system or
- installing harmonic filtration equipment to eliminate system issues.

To manage harmonics may require either strengthening which may include increased neutral wire size, installation of transformers that are K-rated, installation of circuit breaker that are harmonic rated. Harmonic suppression equipment currently on the market includes passive or active harmonic filtering, isolation transformers and harmonic suppression systems. Such equipment varies in cost but active filters are the most effective yet most expensive option. A detailed study of system is required to ensure the correct placement of harmonic suppression equipment.

Chapter Conclusion : Distribution power quality engineers are responsible for the QOS on the respective networks and need to also have an influence on large scale CFL roll out programmes especially on networks already close to the harmonic limits. The Network Engineers will also have a responsibility and a role to play on behalf of the utility to influence the lighting industry standards considering that the SA standard is currently silent on CFLs harmonic standards. If it is not possible to influence the use HPF CFLs upfront or limit the penetration of LPF CFLs on identified sensitive networks then network solutions for strengthening or harmonic suppression is a post CFL deployment remedy that could be implemented.

CHAPTER 6: CONCLUSION

The specific objectives set out to answer the research questions have been addressed as shown in the table below :

Table 6-1 Summary of specific objectives of study

Specific Objectives of Study	Objectives Addressed and Where ?
Establish if the CFL standards currently utilised are adequate enough to mitigate the negative impact on power quality which more specifically relates to harmonics.	Yes, chapter 2.5.4
Identify appropriate international harmonics standards that are applicable to mitigate the negative impact on power quality.	Yes, chapter 2.4.1
Conduct laboratory tests to establish whether the commercially available CFLs meet the standards required to minimise the negative impact on power quality.	Yes, chapter 3
Review relevant literature and case studies to establish the impact of large scale CFL deployment on power quality	Yes, chapter 4
Establish the role of utility power engineers in mitigating the negative impact of large scale CFL deployment on power quality.	Yes, chapter 5

1. All the CFLs tested irrespective of quality and brand reputation have all complied to South African standard, SANS 60901/IEC 60901 by meeting PF requirements i.e. PF > 0.5 (leading), but all failed with compliance to the IEC 61000-3-2 limitations i.e. PF > 0.96. The HPF lamp was significantly closer to the IEC 61000-3-2 limitations at 0.93. Refer to figure 3-54 for summary of batch 1 laboratory tests conducted.

2. The HPF (high power factor) CFL tested met all the lower frequency IEC 61000-3-2 current harmonic requirements and also comes very close to meeting the THD (total harmonic distortion) requirement and can be recommended for large scale CFL rollouts without a need for consultation with the network plant engineer responsible for the respective network. Refer to chapter 3.5.2 and chapter 3.5.3 for the summary of CFLs tested.

3. All the LPF (low power factor) CFLs tested irrespective of quality standards compliance and brand reputation have failed with compliance to IEC 61000-3-2 limits specifically i.t.o. THD, low frequency harmonics (mA/W and percentage of fundamental) and may pose a risk on networks already experiencing power quality issues. The THD for LPF CFLs tested ranged between 105% to 122% which is higher than the prescribed IEC 61000-3-2 limit of 33%. Refer to figure 3-50 and figure 3-51 for the summarised graphical representation of CFLs tested.

4. The increased market penetration of CFL's suggests that power quality issues are expected to rise from the resulting increase in harmonic levels more especially on networks that are already near the harmonic limitations. Utility engineers will have to play a more active role in the large scale CFL programmes. Refer to chapter 5.5 for the role that the utility's power quality engineer can play to enforce CFL standards, manage harmonic penetration levels and deploy mitigation network solutions on sensitive networks to manage the network impact of large scale CFL deployment.

5. Laboratory Batch 2 tests have indicated that CFLs current harmonics could cancel each other when interacting with other types of non-linear loads in certain instances like shown in chapter 3.6 and graphically illustrated on figures 3-55 and figure 3-56.

6. These laboratory studies have also revealed the importance of the presence of linear resistive loads to dampen harmonic levels of CFLs within IEC limits like shown in chapter 3.6 and graphically illustrated on figures 3-55 and figure 3-56.

7. Existing lighting industry CFL standards have gaps pertaining to specifications relating to harmonics and PF as prescribed in the IEC 61000-3-2 to mitigate any possible adverse impact on power quality. The utility engineers have a responsibility to influence the adoption of this IEC 61000-3-2 standard to manage any possible adverse impact on power quality within specific networks. Refer to chapter 2.5.4 for more detail on lighting industry CFL standards.

8. Field studies and simulations in chapter 4 reveal that the introduction of non-linear equipment on the network induces harmonic current flow. The replacement of ILs with energy efficient lamps results in a desired reduction of network load however it also inject harmonics which may result in an overloading of the protective earth neutral conductor in a 3 phase (star) network. Refer to section 4.2. for a more detailed discussion.

9. Field studies and simulations in chapter 4 also reveal that the voltage THD is mostly determined by the distribution transformer's impedance. These studies have also highlighted that the CFLs total active power should be limited to 10% of the rated transformer power as in the case study of the commercial building trying to contain the voltage THD on the busbars within the IEC/TR3 61000-3-6 limits.

10. Special precaution to be taken when applying CFLs to network with weak voltage or perhaps supplied by photovoltaic (PV) system especially now with the introduction of the Independent Power Producers (IPPs) with renewable energy sources like PV and wind power. Refer to chapter 4 for more detailed discussion.

11. Globally CFLs play a very crucial shorter term role as a demand side solution addressing the power crisis while longer term capital intensive supply side solutions are unfolding. Refer to section 2.2 for a more detailed discussion.

CHAPTER 7: RECOMMENDATIONS

1. Considering the high volume of CFLs entering the market, there needs to be tighter controls on the quality standard of CFLs from the lighting industry and the utility implementing large scale CFL rollout programmes. Existing local and international quality standards need to be thoroughly and regularly reviewed to ensure that the IEC61000-3-2 harmonic limits requirements are also included.

2. Given the nature of the CFL's i.t.o. harmonics and power factor, it important that utility network engineers responsible for supply quality be consulted prior to large scale rollouts in the specific poor performing networks. This implies that the utility network engineers should request for compliance to the IEC61000-3-2 requirements prior to the procuring of CFLs in problematic networks i.e. networks that are already closer to their harmonic limits. Refer to chapter 5.5 for the role that the utility power quality engineer can play to mitigate and manage the impact of large scale CFL deployment on power quality.

3. The additional cost differential for ensuring that the CFLs utilised are IEC61000-3-2 compliant in large scale rollout programmes would require exploring joint budgeting possibilities from the respective Distribution network QOS department. This will ensure that the respective QOS engineer would then have a more upfront pro-active role in such rollout programmes rather than trying to reactively and/or sporadically trying to manage the network voltage THD compliance to applicable standards (i.e. IEEE standard 519 or IEC 61000-3-6) or even worse if only alerted when the impacted customers eventually start complaining about poor quality of supply.

4. Further independent field network studies are required to better understand the impact of these devices under various network conditions (eg. PV/Wind embedded generation, weak voltage networks) w.r.t. harmonics and power factor. More especially within poor performing networks down to a rural sub-system including situations with possible mixed industrial loading. Understanding the impact on specific network types will empower the power quality engineer to better manage the impact on power quality.

5. All future low income area CFL sustainability programmes should be used as an opportunity to phase out non-compliant LPF CFLs with the IEC 61000-3-2 compliant CFLs, HPF CFLs or any alternative cost effective efficient lighting solution complying to IEC 61000-3-2 with minimal impact to power quality.

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Further Related / Relevant Reading

Illumination Levels

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HPF CFLs

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