Domestic Lamp Replacement Project

Technology Impact Assessment

Econnect Project No: 1964

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1 Executive Summary

In February 2007 the Commonwealth Government announced that Australia would phase out the use of ordinary incandescent (GLS) light globes by 2010, in favour of compact fluorescent lamp (CFL) technology. In light of this announcement, Sustainability Victoria is considering a promotional programme of providing up to one million free CFLs to Victorian households.

A significant issue for the programme is the impact on the Victorian electricity network of the widespread replacement of GLS lamps with CFLs. The potential for significant adverse impacts is considered to arise from waveform distortion (harmonic) emissions, as well as from low power factors (PF).

Since the issue became prominent in the early 1990s, a number of studies have considered the impact of CFLs on power quality in distribution networks. These studies have varied a great deal in their conclusions, largely resulting from differences in key assumptions made. Conclusions to the effect that CFLs pose significant issues for distribution utilities often stem from considering atypical scenarios where CFLs form the majority of the load on distribution feeders, where network parameters and loadings are not held constant when substituting CFLs for GLS lamps, or where the reduction in lighting power demand is not taken into account.

An assessment has been undertaken based on a model that reproduces key features of a typical medium voltage (MV) distribution feeder and its associated low voltage (LV) feeders supplying predominantly residential load. A model was constructed in harmonic load flow simulation software, taking into account the behaviour of conductors and transformers at harmonic frequencies and the spatial distribution of customer loads. Particular attention was given to the consequences of CFLs on thermal loading, power flows, steady-state voltages, and harmonic voltage distortion in the network.

The assessment reveals that the replacement of GLS lamps with CFLs:

1. Reduces the level of current flowing in the distribution network, and accordingly the thermal loading and losses in feeders.
2. Reduces both the peak power demand and the apparent power flow in kVA in the MV and LV feeders.
3. Reduces the voltage regulation on the feeders, hence reduces the potential for exceeding the ±6% voltage envelope required under the Victorian Distribution Code.
4. Increases the level of harmonic voltage distortion. For the proposed scenario of replacing one GLS lamp in each of one million households, the increase in voltage distortion is not significant. When replacing all GLS lamps with CFLs of the LPF variety, the potential for unacceptable voltage distortion depends on the background level of voltage harmonics already existing in the network. If the background harmonics are already close to the 5% limit in the Victorian Distribution Code, the contribution from wholesale replacement of GLS lamps with LPF type CFLs may raise voltage distortion above the limit. However, the contribution of even LPF lamps alone is not sufficient to cause voltage distortion to exceed regulatory limits.

It is concluded that the proposed programme of offering CFLs to one million Victorian households can proceed without detrimental impact on Victorian power distribution networks, regardless of whether LPF or HPF lamps are offered.

The future scenario, where all lamps are replaced with CFLs, can proceed with caution. If HPF lamps are widely used in future, the harmonics issue posed is unlikely to be significant compared with that posed by other electronic appliances. However if LPF lamps continue to be used to the point where they achieve penetration close to 100%, then CFLs need to be considered among the other significantly distorting equipment that includes variable-speed air conditioners, computers, audio-visual appliances, and newer whitegoods that employ variable-speed drives. All such equipment contributes significantly to harmonic distortion and thought must be given to the possible mitigation measures. Among those more usually considered, embedded generation on the household scale provides opportunities to mitigate harmonics by reducing the distance through which harmonic currents must propagate through networks.

2 Introduction

2.1 Background

In February 2007 the Commonwealth Government announced that Australia would phase out the use of ordinary incandescent (GLS) light globes by 2010, in favour of compact fluorescent lamp (CFL) technology. In light of this announcement, Sustainability Victoria is considering a promotional programme of providing up to one million free CFLs to Victorian households.

A significant issue for the programme is the impact on the Victorian electricity network of the widespread replacement of GLS lamps with CFLs. The potential for significant adverse impacts is considered to arise from waveform distortion (harmonic) emissions, as well as from low power factors (PF).

A specification has been developed for the supply of CFLs into this promotional programme. The specification states that the power factor (PF) must be 0.5 or greater. This is a less stringent requirement than that set by the New Zealand Electricity Commission, which requires CFLs in that country to have a PF of 0.9 or greater and comply with the harmonic emission limits set by IEC 61000–3–2. At this stage Sustainability Victoria has not identified a necessity for these more stringent requirements, and understands that many CFLs on the market in Australia have power factors as low as 0.5 (so-called Low Power Factor or LPF lamps).

Sustainability Victoria has obtained advice from CFL manufacturer Philips to the effect that neither LPF lamps nor High Power Factor (HPF) lamps have been shown to have any significant or detrimental effects on power systems where they are in common use.

In light of the above, Sustainability Victoria needs to clarify whether and under what conditions and lamp specifications there would be any *significant* detrimental impact on the Victorian electricity system, or on Distribution Network Service Providers (DNSPs). Of prime interest is any significant network or electricity system impact that may create reason for concern from DNSPs, due to the power factor of typical CFLs on the market and harmonics from electronic ballasts.

2.2 Scope of Work

In light of the above, Econnect has been engaged to perform the Scope of Work detailed below in support of a potential roll out of a CFL replacement programme by Sustainability Victoria.

The Scope of Work will include: -

1. Brief review of CFL technologies in use in the Australian domestic marketplace.
2. Development of models and/or methods for assessment of power system impacts of lamp replacement, considering applicable standards including IEC 61000–3–2.
3. Indicative analysis and assessment of the power system impact of a range of lamp replacement scenarios.
4. Identification of any significant detrimental impacts of the analysed scenarios on DNSP feeders and networks relative to the GLS 'base case', in regard to harmonic emissions, thermal loading, active and reactive power flows, and steady state voltage.
5. Indicative quantification of power system impacts of CFLs in relation to those of other loads commonly found in DNSP networks.

More specifically, the following lamp replacement scenarios will be considered: -

A. Replacement of a single GLS lamp with a single CFL in approximately one million households spread broadly across Victorian distribution networks.

B. Replacement of all GLS lamps with CFLs in all households throughout Victoria.

Each of the above scenarios will consider separately the effect of replacement with HPF lamps and with LPF lamps.

The Scope of Work entails the following assumptions: -

- Each GLS lamp is rated at 60 watts and is replaced with a CFL of rating 11 watts or higher.
- Each household studied is deemed to contain 15 GLS lamps.
- The lighting types considered are restricted to GLS lamps and CFLs.
- The power factors and harmonic emission characteristics of the lamps studied will be determined from Econnect's assessment of the available technologies.

3 Technology Overview

3.1 GLS (Incandescent) Lamps

Ever since electricity was first used for lighting homes on a broad scale, the dominant electric lighting technology has been the so-called General Lighting Source (GLS) incandescent lamp.

The GLS lamp operates in a very simple manner by passing current through a filament within a globe filled with inert gas. The filament presents itself to the power supply as almost a pure resistance, so that when operated on an AC supply the lamp draws a relatively undistorted AC current in phase with the voltage. Accordingly, from a power quality perspective the GLS lamp is relatively benign, with a high power factor and low current distortion.

The enduring popularity of the GLS lamp arises from its low cost, its robustness and its agreeable luminous qualities, producing a warm light with good colour rendering. However, because the light source relies on radiation from a heated filament, around 95% of the input energy to the lamp is dissipated as heat (infrared radiation) rather than visible light. GLS lamps accordingly suffer from high energy consumption relative to actual light output.

3.2 Compact Fluorescent Lamps (CFL)

Gas discharge lighting relies for its operation on the creation of an ionised gas or plasma within a tube. Free electrons within the gas collide with suspended atoms and transfer energy to the electrons bound within the atoms. These bound electrons are placed in an 'excited state' and subsequently fall back to their 'ground state', emitting radiation in the process. With a sufficient concentration of suspended atoms of the right type, this process can be made quite efficient.

The 'fluorescent lamp' is a type of gas discharge lamp that operates with low internal gas pressure. The emitted radiation is usually in the ultraviolet part of the spectrum, and is converted to visible light by means of a phosphor coating on the tube surface, which fluoresces (absorbs photons and re-emits them at higher wavelengths). Early fluorescent lamps were bulky and produced a relatively 'cool' light toward the blue end of the spectrum, but improvements in technology have allowed the packaging to be made much more compact and the quality of light to be improved. The result is the so-called Compact Fluorescent Lamp (CFL), contemporary versions of which provide 'light warmth' and colour rendering comparable to that available from GLS lamps.

The initial production of the ionised gas in the fluorescent tube requires the application of a high voltage to a heated electrode, but once established, operation can be sustained at low voltage and lower temperature. As a result, CFLs are a good deal more efficient than GLS lamps, requiring some 20% of the input power for the same light output. This makes CFLs a very attractive alternative to GLS lamps from the perspective of reducing energy use and greenhouse gas emissions associated with domestic lighting. Steady reductions in the price at which CFLs can be made available on the market mean the initial purchase price is no longer the barrier it was a decade ago.

From an electrical perspective, a gas discharge lamp is a negative-resistance device, so cannot be operated directly from a constant-voltage AC or DC supply in a stable manner. The lamp itself is always operated via an auxiliary 'ballast' circuit whose purpose is to regulate the current flow into the tube. In modern fluorescent lamps, including CFLs, ballasts are of two main types:

- **Magnetic ballasts** place a large AC inductor in series with the lamp. This provides a large impedance which limits the input current, without the substantial losses a series resistor would entail. However, the inductor does incur some additional losses due to winding resistance and eddy currents, reducing the overall efficiency of the lamp. The large series reactance also entails a low power factor. A shunt capacitor is sometimes used to correct the power factor, but this adds to cost and bulk.

- **Electronic ballasts** use an inverter to synthesise a high-frequency AC current which is fed to the lamp. The inverter provides the necessary current limiting function, and the high frequency avoids the 100Hz flicker to which magnetically ballasted lamps are susceptible. The inverter operates from a DC source, which is obtained from the AC supply usually through a diode bridge rectifier with a filter capacitor on the DC side. This capacitively-smoothed rectifier is a source of significant current distortion, as the input current to such a device tends to consist of periodic short pulses rather than a smooth sine wave. The presence of current distortion also reduces the input power factor, since only the fundamental 50Hz current contributes real input power but the RMS current is significantly greater than the fundamental. Again it is possible to reduce the current distortion and raise the power factor with additional filter circuits on the input, but this adds to the overall cost.

Electronic ballasts have largely replaced magnetic ballasts in contemporary CFLs, for many reasons including reduced size and weight, higher efficiency, improved lamp performance and the absence of unpleasant side effects such as flicker and hum. However, electronic ballasts are considered to have a more severe power quality impact than magnetic ballasts due to their high distorting currents. For these reasons this report focusses primarily on CFLs with electronic ballasts.

Due to the power quality side-effects mentioned above, both magnetically and electronically ballasted CFLs are sold in so-called high-power-factor (HPF) and low-power-factor (LPF) versions. HPF lamps are characterised by a power factor in excess of 0.9 and by low current distortion, achieved by means of filters or power-factor-correcting capacitors. LPF lamps achieve a lower manufacturing cost and slightly higher efficiency by avoiding the use of filters, but have power factors typically close to 0.5, and if electronically ballasted can have total harmonic current distortion in excess of 100% of the fundamental.

Because of their cost advantage relative to HPF lamps, LPF lamps are likely to play a significant role as replacement light sources in the planned phase-out of GLS lamps in Australia.

3.3 Power Quality Impact of CFLs: Prior Studies

Since the issue became prominent in the early 1990s, a number of studies [3,7,9,12,14,15,16,19] have considered the impact of CFLs on power quality in distribution networks. These studies have varied a great deal in their conclusions, largely resulting from differences in key assumptions made. Conclusions to the effect that CFLs pose significant issues for distribution utilities often stem from considering atypical scenarios where CFLs form the majority of the load on distribution feeders, where network parameters and loadings are not held constant when substituting CFLs for GLS lamps, or where the reduction in lighting power demand is not taken into account.

Studies that have considered CFL replacement scenarios within the context of actual network loads on large grids [19] have tended to conclude that even with wholesale replacement, the additional harmonic distortion is within acceptable limits provided lighting represents no more than around 10 to 20 per cent of the average customer load.

Lighting manufacturers have undertaken their own studies and presented field data [13] in support of their case that when the balance of the domestic load and the reduced power consumption of CFLs compared to GLS lamps is taken into account, the power quality impact on distribution feeders from CFLs is not significant, whether HPF or LPF lamps are considered.

Other studies do however suggest that distribution utilities should be cautious in certain cases. Vigilance is required when installing large numbers of CFLs in weak energy-constrained networks [7] and in large commercial premises with high lighting demand such as hotels [15].

3.4 Performance Standards for CFLs

As CFLs have become more widely marketed, concerns have arisen about the accuracy of manufacturer claims concerning energy consumption, lighting performance and lifetime of CFLs. In response, most jurisdictions including Australia have made or are considering Minimum Energy Performance Standards (MEPS) for CFLs and fluorescent lamps in general. In some cases these MEPS also impose mandatory compliance with power quality standards.

In Australia only linear fluorescent tube lamps are currently covered by MEPS [17] but it is planned to extend coverage to CFLs under the 'GreenLight Australia' initiative. An assessment report on MEPS options for CFLs [8] has proposed a minimum power factor of 0.5 as a mandatory standard and 0.9 as a voluntary 'high efficiency' standard, reflecting the current market segmentation into LPF and HPF devices. The proposed MEPS does not include any specific requirement for harmonic distortion, but it should be understood that any minimum requirement for power factor contains an implicit requirement for harmonics (in particular it is unlikely with prevailing technology that an electronically ballasted CFL would meet a 0.9 power factor standard without harmonic filtering). The GreenLight strategy foreshadows that the high-efficiency standard may become mandatory in the future, which would entail a phasing out of LPF lamps.

A more stringent MEPS has been adopted for CFLs in New Zealand, which mandates a minimum power factor of 0.9 and harmonic emissions compliant with AS/NZS61000.3.2, which prescribes limits for lighting equipment on individual harmonics of order 2 and all odd orders [18].

4 Model Development and Assessment Scenarios

4.1 Distribution Network Model

The present study considers the impact on distribution networks of replacing GLS lamps with CFLs in residential environments. Accordingly, assessment is based on a model that reproduces key features of a typical medium voltage (MV) distribution feeder and its associated low voltage (LV) feeders supplying predominantly residential load. A model was constructed in harmonic load flow simulation software using as the base case the following network configuration:

- Grid infeed: 500MVA fault level at 66kV, with X/R ratio of 6 to 1.
- 66/22kV zone substation: 2 x 30MVA transformers, series impedance 12% on 30MVA base, resistance insignificant. Shunt magnetising admittance of (1 + j3)% on 30MVA base.
- 10 x 22kV MV feeders supplied from the substation, of which one feeder is modelled in detail. The effect of harmonic propagation between separate MV feeders is neglected as previous studies indicate that MV feeders are less affected by harmonics than LV feeders.
- MV feeder supplies 10 distribution transformers over a distance of 20km. (This is longer than typical in urban areas, but was selected to give a high feeder impedance conducive to the production of voltage harmonics.) Line impedance is (0.2 + j0.4) ohms per km and capacitance is 0.1 µF per km.
- Distribution transformers are of vector group Dyn11 or similar, with a typical nameplate rating of 500kVA and a short term rating of 1MVA. Series impedance is 6% on the transformer rating. This specification is typical for distribution transformers used in Victoria but implies that triplen harmonics (3^{rd}, 6^{th}, 9^{th} etc.) cannot propagate from the LV network to the MV network. Distribution transformer ratings in the field range from 10kVA up to 5MVA.
- Each LV feeder supplies 90 households over a distance of up to 1km. Line impedance is (0.1 + j0.2) ohms per km and capacitance is 0.1 µF per km. Load was assumed to be evenly distributed between the three phase conductors.

To achieve a reasonable level of accuracy for the medium-frequency network impedances, the approach in [11] was followed when modelling all feeder sections.

4.2 Household Model

Available surveys of Australian household energy use such as [5,1] generally find that lighting accounts for around 10% of electricity use on average, but up to 20% during peak usage periods. Other electronic appliances such as computers, televisions and variable-speed air conditioners account for a further 20% of electricity use. The remainder is mostly for space heating, hot water, refrigeration and non-electronic appliances.

Accordingly the following assumptions are used when modelling households for this study:

- Peak consumption of 4.5kW is assumed for the base case using GLS lamps.
- Lighting is taken to represent 20% of consumption or 900W, notionally broken down as 15 GLS lamps each consuming 60W.
- Electronic appliances other than CFLs are assumed to draw a square-wave current, giving a spectrum of odd-order current harmonics with magnitude 1/h for harmonic order h.

- Non-electronic appliances including GLS lamps are modelled as impedances, with an overall power factor of 0.85.

4.3 CFL Harmonic Spectrum

This assessment considers two broad classes of CFL: a LPF lamp having a power factor of 0.5 and a HPF lamp having a power factor of 0.9. In highly nonlinear devices such as CFLs, the reduction in power factor from unity is predominantly due to the presence of current harmonics ('distortion factor') rather than the more usual phase shift between the fundamental current and voltage ('displacement factor'). The distortion factor (DF) is related to the total harmonic current distortion (THD) by the following formula:

$$THD_I = \sqrt{\frac{1}{DF^2} - 1}.$$

It follows that for a lamp with a power factor of 0.5 the maximum current THD is 173%, while for a lamp with a power factor of 0.9 the maximum THD is 48%.

Measurements of the harmonic spectrum of CFLs can be undertaken with a power quality analyser, and several such measurements have been reported in the research literature. These are broadly similar to one another, reporting a level of third harmonic comparable to that of the fundamental, and levels of higher odd harmonics that decrease gradually from the fifth to the nineteenth order. Even-order harmonics are generally found to be insignificant, as may be expected given that the operation of rectifiers generally produces current waveforms with approximate half-wave symmetry [10].

The harmonic spectrum used for CFLs in the assessment model is a scaled version of that reported from measurements on 20W CFLs in [Korovesis2004]. The original measurements indicate a level of current THD around 130%. In the model, the individual harmonic magnitudes have been uniformly scaled to a THD of 173% for the LPF lamps, and to 48% for the HPF lamps. **Figure 1** shows the resulting harmonic spectra for both CFL types.

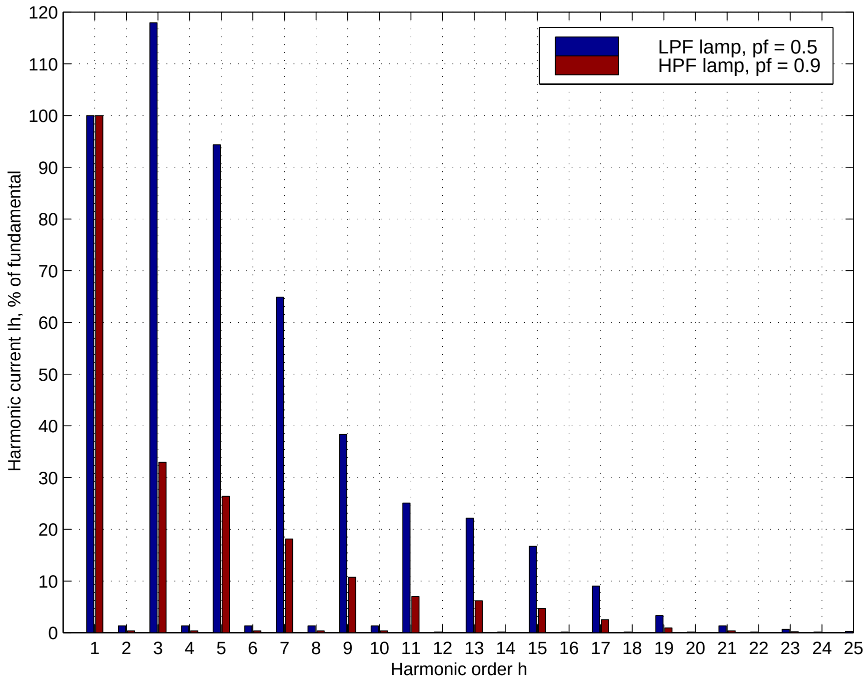

Figure 1: Harmonic spectrum of CFL currents as modelled

4.4 Scenario Modelling

The assessment calls for the investigation of CFL replacement for (A) one lamp in one million households across Victoria and (B) all lamps in all households in Victoria.

ABS estimates [2] place the number of Victorian households at almost exactly 2 million in 2007/08, meaning that scenario A corresponds to replacing one lamp in 50 per cent of households. On a distribution feeder with 900 households as modelled, lamps will be replaced in an *average* of 450 households, but the actual number of households will vary from feeder to feeder if CFLs are distributed ‘at random’. Nonetheless it is 98% probable that on a feeder with 900 households, at most 480 will receive replacement lamps.

In terms of distribution system impact, a likely ‘worst case’ is for the replacement to occur in households at the more remote ends of the LV feeders. Accordingly, Scenario A is modelled for each of the 10 LV feeders by replacing one 60W GLS lamp with one 12W CFL in each of the 48 households located toward the remote end, and leaving the remaining 42 households unchanged. This will represent a credible worst case impact for a Victorian DNSP under a ‘one million households’ replacement scheme.

For scenario B, the entire 900W assumed lighting load (15 x 60W GLS) was replaced with 180W of CFL load (15 x 12W) in each of the 900 households in the modelled distribution feeder.

5 Results and Discussion

5.1 Thermal Loading

Table 2 shows, for each of the scenarios studied, the RMS current entering the MV feeder at the zone substation and the current on the LV side of a distribution transformer.

Scenario	CFL power factor	Current in MV feeder (A)	Current in LV feeder (A)
Base case		136	738
A: Replace one lamp in one million households	0.5	135	728
	0.9	135	728
B: Replace all lamps in all households	0.5	117	636
	0.9	116	635

Table 2: Thermal loadings (total RMS current) resulting from CFL replacement

In each of the considered scenarios it can be seen that the current in the MV and LV feeders is reduced relative to the base case, and is lowest when all lamps are replaced. This reflects the fact that despite CFLs having a lower power factor than GLS lamps, the reduced energy consumption leads to a lower current demand overall.

It is actually apparent from **Table 2** that the reduction in current is barely sensitive to the power factor of the lamps. This is a consequence of the low power factor being due to harmonic distortion rather than to a phase shift of the fundamental current. Although the RMS currents reported here include contributions from harmonic currents as well as from the fundamental, the harmonic currents are rapidly attenuated as they propagate through the network.

5.2 Network Power Flows

Table 3 shows, for each of the studied scenarios, the active power and the apparent power (product of RMS voltage and current) at the zone substation and a distribution transformer.

Scenario	CFL power factor	Real power (kW)		Apparent power (kVA)	
		MV feeder	LV feeder	MV feeder	LV feeder
Base case		4779	435	5781	543
A: Replace one lamp in one million households	0.5	4676	425	5651	531
	0.9	4676	425	5651	531
B: Replace all lamps in all households	0.5	4125	379	4910	471
	0.9	4126	380	4905	470

Table 3: Real and apparent power resulting from CFL replacement

It is evident from **Table 3** that the replacement of GLS lamps with CFLs reduces both the real and the apparent power flow in the network. Again, the reduction is greatest when all lamps are replaced: in fact the saving in power consumption from replacing all GLS lamps with either HPF or LPF lamps is around 14 per cent of total peak demand with the assumptions used.

There is a lack of consensus within the industry as to how 'reactive power' ought to be defined in the presence of significant harmonic distortion. While active power (rate of energy consumption) and apparent power have unambiguous definitions regardless of the level of distortion, reactive power has traditionally been defined by reference to the behaviour of undistorted sinusoidal voltages and currents at a single frequency.

Ambiguity in the definition of reactive power for non-sinusoidal quantities has led to confusion, particularly in regard to the relationship between reactive power and power factor. When distortion is absent, low power factors arise purely from the phase difference between sinusoidal voltage and sinusoidal current, and it is possible to define a unique quantity which is generated in capacitors, consumed by inductors, and conserved across the network as a whole. However, this theory breaks down in the presence of significant distortion. When distortion is present, the power factor of a load will be reduced by the distortion itself, and the standard remedy for low power factors – the installation of correcting capacitors – does not directly address this issue and may instead reduce the power factor further by increasing the level of harmonics.

An incomplete understanding of this issue appears to underlie the conclusion of early studies such as [14] which predicted very high levels of harmonic distortion from even partial installation of CFLs. The authors in [14] assumed that any installed CFLs would have to be 'compensated' by additional shunt capacitors in the network due to their low power factors. Other studies such as [19], that did not assume the addition of capacitors to the network, predicted much lower levels of harmonic distortion.

In the sinusoidal picture, the reason it is desirable to correct for low power factors is that the excess reactive power would otherwise have to be supplied remotely by generators, and the large distance between the production and consumption of reactive power causes the network currents to be higher than necessary (and may also lead to voltage issues). On the other hand, when low power factors are due to harmonics, there is no conserved quantity that must be supplied by a generator, and passive elements within the network will tend to filter the harmonics before they can propagate far into the transmission system.

Rather than attempt to weigh the merits of various definitions of reactive power, we believe it sufficient to state that according to **Table 3** the real and apparent power flows are reduced as a consequence of lamp replacement. This indicates that lamp replacement is unlikely to pose issues of the kind that result from excessive flows of reactive power, except those directly arising from increased harmonic distortion as discussed in Section 5.4 below.

5.3 Steady State Voltage

Table 4 shows, for each of the modelled scenarios, the maximum and minimum per-unit voltages seen on LV feeders.

Scenario	CFL power factor	MV feeder voltage (%)		LV feeder voltage (%)	
		Maximum	Minimum	Maximum	Minimum
Base case		106.76	102.50	105.93	94.58
A: Replace one lamp in one million households	0.5	105.74	101.54	105.93	94.66
	0.9	105.74	101.54	105.92	94.66
B: Replace all lamps in all households	0.5	105.95	102.35	105.94	96.63
	0.9	105.95	102.35	105.94	96.63

Table 4: Steady state voltage resulting from CFL replacement

It is seen that the replacement of GLS lamps with CFLs slightly reduces the voltage regulation, or difference between the maximum and minimum feeder voltage, on both the LV and the MV feeder. Again, this is an indirect consequence of the reduced power consumption of the CFLs relative to GLS lamps. Since voltage regulation is quite sensitive to power flow under peak demand conditions in LV networks, the 14% reduction in peak energy consumption from replacing all lamps is sufficient to provide an 18% reduction in LV feeder voltage regulation. Again, the change in voltage regulation is not sensitive to the CFL power factor.

5.4 Harmonic Emissions

Table 5 shows the maximum voltage THD recorded in the modelled network under each of the scenarios studied, as well as for the base case.

Scenario	CFL power factor	THD due to CFLs (%)	Overall THD (%)
Base case			4.09
A: Replace one lamp in one million households	0.5	0.14	4.22
	0.9	0.04	4.13
B: Replace all lamps in all households	0.5	2.90	6.88
	0.9	0.81	4.92

Table 5: Harmonic emissions resulting from CFL replacement

Due to the fact that a realistic estimate has been included of harmonic emissions due to electronic appliances other than lighting, the background level of voltage THD is quite high: around 4% compared with the limit of 5% set for distribution networks in the Victorian Distribution Code [4]. This leaves relatively little 'headroom' for additional distorting loads before it is necessary to contemplate corrective action.

Table 1 nonetheless shows that, despite this fairly pessimistic estimate of existing background harmonics, the contemplated Scenario A of replacing one million lamps in one million households can be accommodated within the network without significant impact on harmonic levels. Even for LPF lamps in this scenario the net impact on voltage harmonics at the worst affected location is less than one-sixth of one per cent.

Scenario B, where all existing GLS lamps in households are replaced with CFLs, can also be accommodated when HPF lamps having a minimum power factor of 0.9 are used. The impact on voltage THD in this case is significant, though still below 1% at the worst affected location.

In the scenario where all GLS lamps are replaced with LPF lamps, the net impact on voltage THD at the worst affected location is just under 3%. When combined with the estimated background level of 4% voltage THD, the resulting distortion exceeds the limits in the Distribution Code. Accordingly, this initial assessment suggests that a wholesale replacement of lamps with LPF models may pose an issue for distribution NSPs. It is important to recognise however that the issue is not posed by CFLs *per se*, but rather by the combination of CFLs and a high harmonic background.

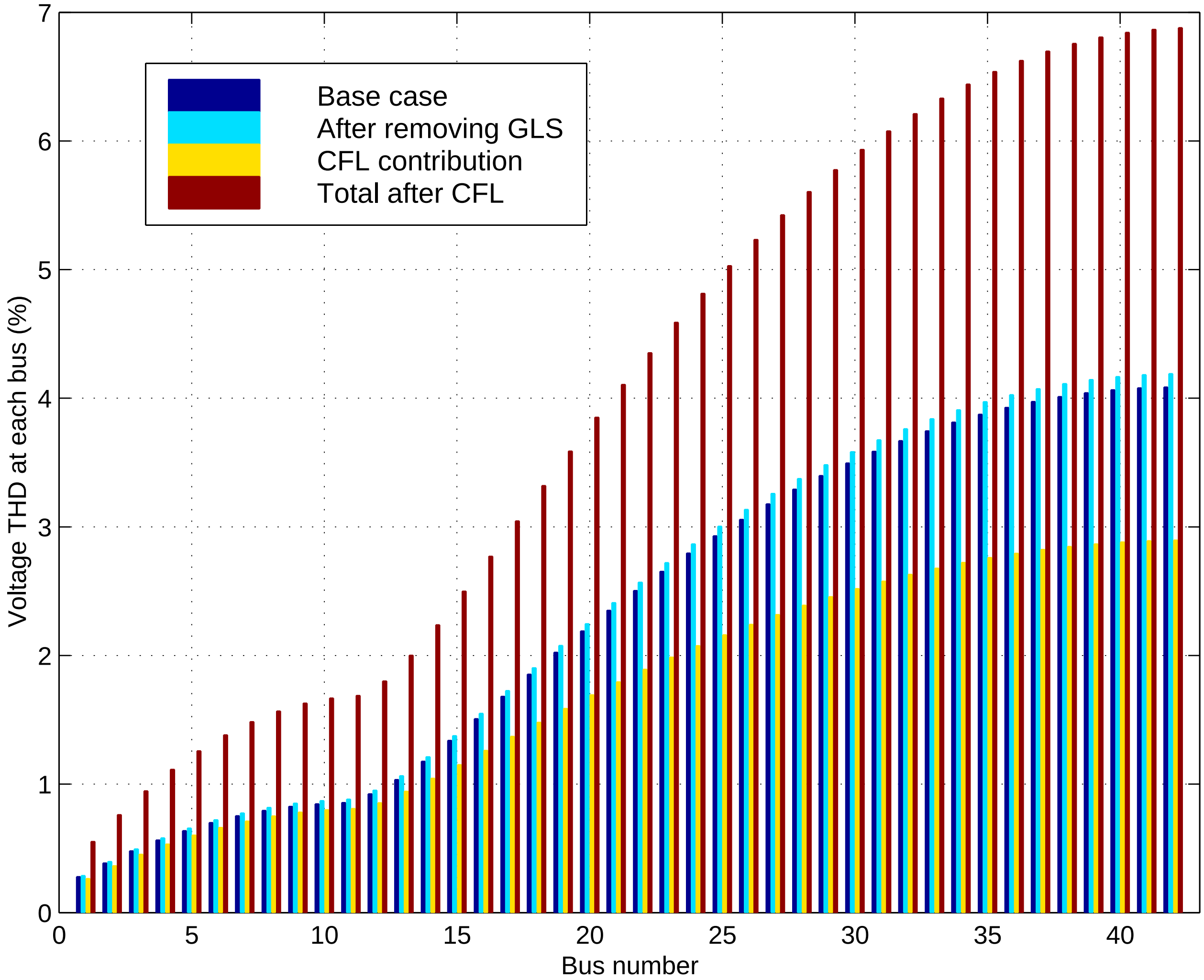

Figure 2: Harmonic profile of MV and LV feeders for Scenario B with LPF lamps (Zone substation is bus 1; distribution transformer is bus 11)

Figure 2 shows a harmonic profile of the feeder as one travels from the zone substation to the end of the MV feeder, then through the remote distribution transformer and down the LV feeder to the remote end (which is the worst affected location for harmonics). It is seen, consistent with previous studies, that the impact of harmonics is more severe on the LV feeder, particularly toward the remote end where voltage drops are greatest.

Harmonic order	Base case	After removing GLS	CFL contribution	Total after CFLs
3	1.52	1.56	1.10	2.65
5	1.90	1.97	1.86	3.83
7	1.52	1.56	1.42	2.97
9	1.15	1.18	0.81	1.99
11	1.10	1.13	0.62	1.75
13	1.01	1.02	0.59	1.62
15	0.92	0.94	0.47	1.42
17	0.87	0.89	0.27	1.16
19	0.83	0.84	0.11	0.95
21	0.78	0.80	0.04	0.84
23	0.75	0.77	0.02	0.79
25	0.72	0.73	0.01	0.74
THD	**4.09**	**4.19**	**2.90**	**6.88**

Table 6: Individual voltage harmonics at worst affected location for Scenario B (%)

Table 6 provides additional details of the individual harmonic emissions at the worst affected bus. (For both CFLs and existing loads, only odd-order harmonics are significant.) It is seen that the highest level of voltage distortion occurs for the fifth harmonic, not for the third, even though it is the third harmonic that contributes the most distorting current. A likely reason for this is that the delta-star connection in distribution transformers prevents the third harmonic from propagating into the MV network, where there are more opportunities for resonance with network capacitances.

Care should be taken, however, not to overstate the potential for harmonic distortion issues even from wholesale replacement of GLS lamps with CFLs. There are a number of reasons why the harmonic voltage impact is likely to be less than suggested above:

1. It has been assumed that all current lighting installations are GLS lamps, and that there is no current installed base of CFLs, other fluorescent lamps, and other lighting technologies. If replacement of GLS lamps has already progressed to a significant extent, as [1] suggests, then the impact of replacing the remaining lamps will reduce proportionately.
2. The assumptions made for the network configuration have been chosen deliberately to give something close to a worst case. In particular the impedance of the LV feeder has been chosen as the highest possible value that keeps the maximum and minimum voltages within the ±6% envelope required by the Distribution Code. Lower feeder impedances will tend to mitigate the impact on harmonics.
3. The assumptions leading to a 4% background level of voltage harmonics are conservative and arguably pessimistic. Since the contribution from CFLs alone is less than this, Scenario B with LPF lamps could still be accommodated in a network with a lower background level of harmonics.

4. Actual network observations have consistently found actual levels of voltage harmonics to be lower than those predicted in modelling studies. The propagation of harmonics in networks is extremely sensitive to detailed properties of the network, not all of which can be modelled adequately.

If the above estimates of background harmonic distortion due to existing loads are reflected in reality, they suggest the desirability of taking action to mitigate harmonics in LV networks, even without a programme to facilitate installation of CFLs. The background levels described here follow from realistic assumptions about the mix of appliances in Victorian households, and exceed the worst case harmonic contribution seen from household CFLs.

Alongside the usual methods available to mitigate harmonic distortion such as filters, the installation of household-scale embedded generation also provides an opportunity to address the issue of harmonics in LV networks. By placing the source of electric energy close to the load, embedded generation can reduce the amount of harmonic current propagating through networks. Even when the embedded generator is connected through an inverter which produces its own harmonics, contemporary inverter technology provides the capability to actively cancel low-order harmonics by means of inverter switching. While this kind of technology is not yet widespread, it is likely to become more popular in the future.

6 Conclusion

Compact fluorescent lamps are an energy-saving technology with real advantages for power distribution networks as well as for energy savings and greenhouse emission reductions.

An assessment has been undertaken of the impact on a typical residential distribution feeder of the replacement of GLS incandescent lamps with CFLs in households. This required the construction of a detailed model of the medium-voltage and low-voltage feeders, taking into account the behaviour of conductors and transformers at harmonic frequencies and the spatial distribution of customer loads. Particular attention was given to the consequences of low power factors of CFLs on thermal loading, power flows and steady-state voltages in the network, and to the consequences of non-sinusoidal CFL current on harmonic voltage distortion in the network.

The assessment has revealed that the replacement of GLS lamps with CFLs:

1. Reduces the level of current flowing in the distribution network, and accordingly the thermal loading and losses in feeders.
2. Reduces both the peak power demand and the apparent power flow in kVA in the MV and LV feeders.
3. Reduces the voltage regulation on the feeders, hence reduces the potential for exceeding the ±6% voltage envelope required under the Victorian Distribution Code.
4. Increases the level of harmonic voltage distortion. For the proposed scenario of replacing one GLS lamp in each of one million households, the increase in voltage distortion is not significant. When replacing all GLS lamps with CFLs of the LPF variety, the potential for unacceptable voltage distortion depends on the background level of voltage harmonics already existing in the network. If the background harmonics are already close to the 5% limit in the Victorian Distribution Code, the contribution from wholesale replacement of GLS lamps with LPF type CFLs may raise voltage distortion above the limit. However, the contribution of even LPF lamps alone is not sufficient to cause voltage distortion to exceed regulatory limits.

It is concluded that the proposed programme of offering CFLs to one million Victorian households can proceed without detrimental impact on Victorian power distribution networks, regardless of whether LPF or HPF lamps are offered.

The future scenario, where all lamps are replaced with CFLs, can proceed with caution. If HPF lamps are widely used in future, the harmonics issue posed is unlikely to be significant compared with that posed by other electronic appliances. However if LPF lamps continue to be used to the point where they achieve penetration close to 100%, then CFLs need to be considered among the other significantly distorting equipment that includes variable-speed air conditioners, computers, audio-visual appliances, and newer whitegoods that employ variable-speed drives. All such equipment contributes significantly to harmonic distortion and thought must be given to the possible mitigation measures. Among those more usually considered, embedded generation on the household scale provides opportunities to mitigate harmonics by reducing the distance through which harmonic currents must propagate through networks.

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