Lessons for the SSL Industry: Impact of CFLs in Replacing Incandescent Lighting

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Abstract

In recent years there has been a rapid transition towards higher-efficiency lighting technologies, in particular a transition from incandescent bulbs to compact fluorescent (CFL) and light-emitting diode (LED) technologies. Until now, this transition has moved forward assuming that a direct placement of new lighting technologies into an infrastructure designed and tested for incandescent bulbs is inherently safe. This paper discusses some potential concerns of a transition, with an analysis of thermal effects and the effect of adding large numbers of CFLs onto an electrical infrastructure originally designed for incandescent bulbs and other linear loads. Though this work focuses on CFLs, the results are applicable to LED, OLED, and other nonlinear loads using switching power supplies.

Keywords

CFL, compact fluorescent lighting, skin effect, cable de-rating, k factor, NEC (National Electrical Code), three-phase systems, electrical safety.

Introduction

There is an accelerating transition from less energy efficient light sources (*e.g.*, incandescent lamps) to compact fluorescent and, in the near future, LED (light-emitting diode) and OLED (organic light emitting diode) light sources. The transition has been driven by state[1] and federal[2] energy efficiency initiatives, but has been helped by lowering costs for these products. These light source technologies are fundamentally different in the electrical properties they present to branch circuit power supplies in homes, offices, and commercial installations. The potential safety impact of the cumulative effect of such a transition has not been fully explored in either US safety standards or installation codes.

[1] AB 1109 (Huffman) Lighting Efficiency & Toxics Reduction Act, signed into law by Governor Schwarzenegger in October 2007.
[2] The Australian Government is intending to eliminate any light bulbs that have an luminous efficacy of less than 15 lumens per watt (lm/w). http://www.environment.gov.au/settlements/energyefficiency/lighting.html

A basic comparison of incandescent, compact fluorescent lamps (CFLs), and LED/OLED technologies suggest that in the long-term LED technologies will be the preferred solution, with CFLs serving as an interim technology. This conclusion can be substantiated by reviewing the benefits of each technology in terms of efficiency, performance, lifetime, and manufacturability. CFLs and LEDs are much more efficient at producing light than incandescent light bulbs – using 75% less energy per lumen than incandescent bulbs.[3] Therefore, purely from an efficiency standpoint both CFLs and LEDs are expected to eventually replace incandescent technologies. However, CFLs have performance drawbacks, including a relatively long time (one minute or more) to generate full brightness after power is applied, and significant reductions in lifetime when CFLs are repeatedly cycled on and off quickly. These drawbacks may make CFL replacement for incandescent bulbs in some areas of the home undesirable, such as in closets, bathrooms, or anywhere lighting may be used only for a short time. CFLs also are fragile and contain small amounts of mercury, which has been an impediment for consumer acceptance of CFLs due to a concern of mercury exposure should the tube of a CFL shatter. LED and OLED technologies address most drawbacks of CFLs, with LEDs able to better tolerate power cycling without a reduction in lifetime, an ability to deliver full brightness instantly, more mechanically robust, and an absence of mercury. LED and OLED technologies also promise further advances in power efficiencies, lifetimes, and unique configurations (particularly for OLED lighting technologies). Currently, market penetration of LED technologies as a replacement for incandescent lighting is limited by cost, particularly compared to CFL pricing. Therefore, CFLs will continue to be widely used until the cost of LEDs fall to be comparable to CFLs.

CFLs and LED/OLED technologies have fundamentally different electrical behavior compared to incandescent lighting. An incandescent bulb is a resistive load, generating light as a byproduct of heating a resistive element. CFLs and LEDs contain switching power supplies to power the lighting element. Switching power supplies draw power from the electrical distribution system very differently compared to a resistive load, and typically include large capacitances and nonlinear components (such as rectifiers and switching transistors). This results in the generation of harmonics and other noise which is injected into the electrical circuit. This may cause problems due to their interaction with switches, dimmers, lighting controllers, wiring, and power distribution systems. Our research intended to learn more about certain negative safety implications of the substitution of CFLs into places where incandescent light bulbs have traditionally been used. This includes both safety implications of placing CFLs into luminaires intended for incandescent bulbs, as well as the effect of installing thousands of nonlinear loads (such as CFLs) onto the electrical infrastructure of a home or large building. Though the focus of this research was on CFLs, the lessons learned are relevant to LEDs, OLEDs, and other nonlinear loads, which are used in most modern consumer electronic products.

[3] US Environmental Protection Agency, Energy Star Program, see http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=LB

CFLs Replacing Incandescent Bulbs in Luminaires

It has been assumed that CFLs may be used in any fixture designed for incandescent bulbs without issue. However, until now this assumption had not been rigorously evaluated. Our work investigated the effects of the CFL technology on temperatures, on switch contacts, and on dimmers and other lighting controllers. We have concluded that substitution into existing lighting fixtures will result in lower operating temperatures, even if the CFL is upsized compared to the equivalent light output of the replaced incandescent lamp. A key observation in this study was that the warmest CFL was cooler than the coolest incandescent bulb (Figure 1). This result is consistent with the fact that CFLs convert energy to light much more efficiently than an incandescent bulb, and that an incandescent bulb is essentially a heating element where light is a byproduct of the heat generation.

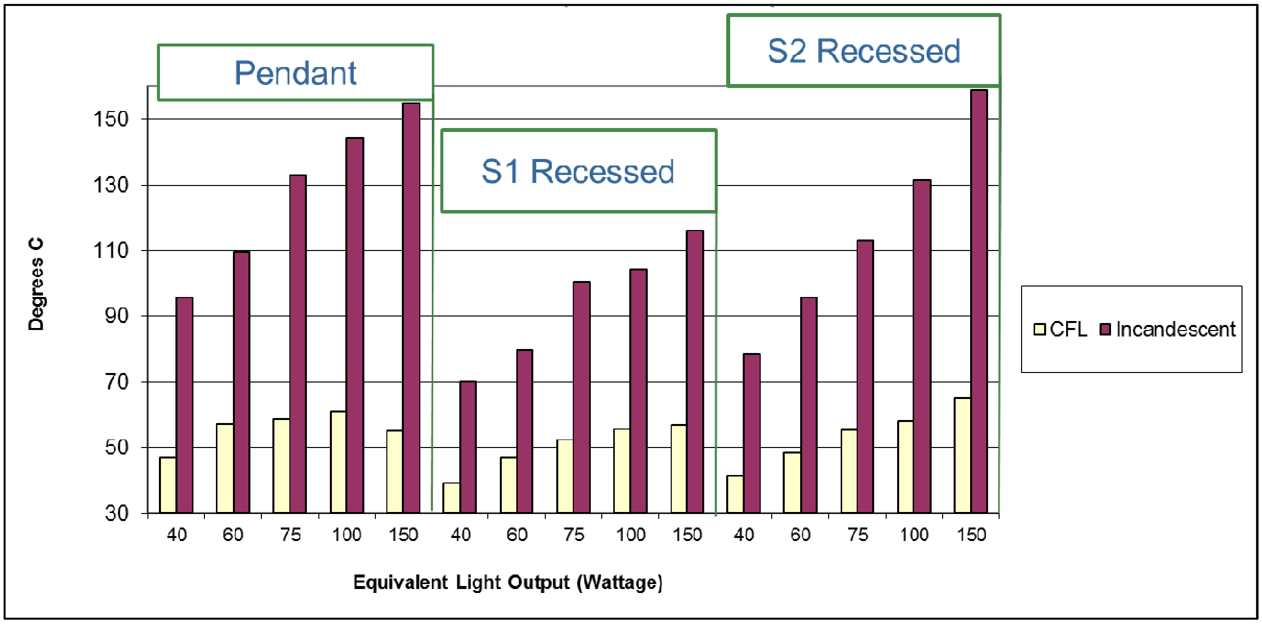

Figure 1. Measurement of the maximum temperature within pendant and recessed lighting for different wattage lighting. In the case of CFLs, the "equivalent light output" is used.

We also observed that CFL lifespan is reduced when used in fixtures where switches are turned off and on repeatedly. Therefore, CFLs may not be a good choice for areas such as closets, where lights may be illuminated for a few seconds. Since we experienced a large number of CFL failures due to the cycling tests, we were able to evaluate typical CFL end-of-life behavior. Our observations have shown that improvements in CFL designs are eliminating end-of-life issues, so that new production CFLs do not have the buzzing noises, odors, or enclosure damage that some consumers experienced in the past. We observed that contact damage in switches connected to a CFL load, due to the high inrush currents, is not significant, and typically shows similar or lower damage relative to an incandescent load after 10,000 switching cycles.

In the area of CFL compatibility with lighting controls designed for incandescent loads, we witnessed occurrences of flickering often accompanied by buzzing noises. However, our results showed no indications of fire, shock, or casualty hazard from any of the CFLs or controllers tested. Despite a lack of evidence of hazards, the potential incompatibility of CFL lamps with incandescent lighting controllers has negative consequences from a marketplace perspective. Consumers expect CFLs (and the LEDs that follow) to integrate seamlessly with existing technology; anything less may become a steady source of frustration for consumers, retailers, and manufacturers alike. In summary, our testing and analysis did not reveal any fire hazards specifically attributable to current-production CFL lamps. More work is underway in the industry to address functional compatibility issues, which would be beneficial from an environmental perspective in encouraging replacement of existing incandescent lamps with CFLs.

Effect of CFLs on Electrical Infrastructure

Another concern with CFLs is their effect on the power supply distribution system when large numbers of CFLs are used. CFLs utilize a switching power supply, which generates significant harmonics (Figure 2): incandescent bulbs, by contrast, do not generate harmonics. The reduced current draw of CFLs also means that the circuit now has unused capacity, which could lead to future changes in power distribution design to make use of this capacity. For example, if it is known that CFLs will be used for lighting instead of incandescent bulbs, more lighting fixtures may be added to a given electrical circuit, taking advantage of the fact that a CFL uses less power. However, this does not consider the fact that higher frequencies will tend to generate more heating per watt than would be observed at 50/60 Hz. Therefore, increasing the total CFL load on a given circuit (for example, placing a full 12A of CFLs onto a residential 15A circuit) will not generate the same amount of heating in the electrical wiring and transformers as would 12A of incandescent bulbs. Therefore, our research focused on the effect of harmonic heating on the electrical infrastructure, particularly whether a safety issue arises when the majority of the electrical load consists of a very large number of CFLs.

CFLs draw electric current in a non-linear way, resulting in a non-sinusoidal current profile. This results in higher frequencies in the current spectrum. These higher frequency components pose several concerns. For example, three-phase currents at 180 Hz, 540 Hz, and higher 'triple N' frequencies cause extra heating in the neutral wire. These currents are shown in the current spectrum chart (Figure 2, right) for harmonic numbers 3, 9, 15, etc. Harmonic heating is also a potential concern in all electrical wiring due to the skin effect. Transformers may also show additional heating when exposed to harmonics, since the inductive elements of a transformer have increasing electrical impedance as the signal frequency increases. These harmonics may also be a source of noise, interfering with powerline telecommunications (including powerline signaling that may be used for smart grid technologies) and the operation of safety equipment, such as ground fault and arc fault circuit interrupters (GFCIs and AFCIs).

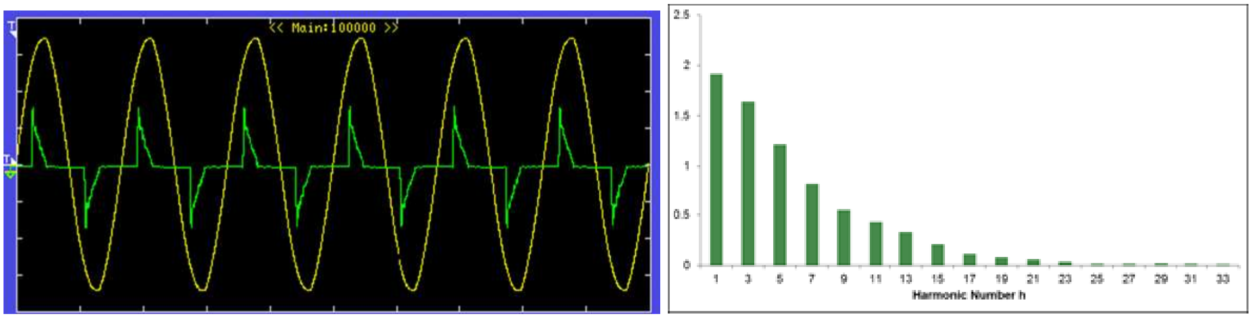

Figure 2. Electrical characteristics of a CFL load. (Left) Time-domain waveform, showing voltage (yellow) and current (green). (Right) Current frequency spectrum for a single CFL.

Skin Effect Heating

Concerns of increased heating of the neural conductor in other non-linear load situations have led to the increase of neutral wire sizing in many installations. For the typical CFL current spectrum, Hiranandani[4] showed the following necessary de-rating of the neutral conductor due to the presence of significant harmonic currents:

Load Current:	*h* = 1 (60 Hz)	350A
	h = 3 (180 Hz)	80A
	h = 5 (300 Hz)	12A
	h = 7 (420 Hz)	12A

According to this work, the line conductor (assuming a gauge of 500 kcmil) must be de-rated by approximately 4%; and the neutral conductor (500 kcmil) by 20%. For nonlinear loads, the theoretical maximum for additional current on the neutral conductor is $\sqrt{3}$ (approximately 1.7) times the maximum current on any phase of a three-phase system.[5,6] Our research continues into determining typical neutral conductor currents for real-world systems as the total electrical load becomes increasingly nonlinear.

Due to the physics of electrical current in wires, the gauge of the conductor is important in determining the effect of higher frequencies on the wire. Using conductor data from Southwire[7] and Okonite[8], it can be calculated that a circuit fully loaded with a single, large nonlinear load supplied by 14 AWG, 12 AWG, or 10 AWG wire would not need any de-rating. As the conductor size increases, the harmonic heating effect increases dramatically, resulting in de-rating of up to 50% for 500 kcmil wire for the same load.

Though this may suggest a serious issue with current wiring practices for large installations, it assumes that the cumulative spectrum for multiple CFLs on a circuit would be

[4] Hiranandani, A.; "Calculation of Ampacities and Sizing of Line and Neutral Conductors in the Presence of Harmonics," *Industrial and Commercial Power Systems Technical Conference, 1995.*

[5] "Hazards of Harmonics and Neutral Overloads," White Paper #26, American Power Conversion, Inc., p.5, 2003.

[6] V.E. Wagner *et al*, "Effects of Harmonics on Equipment," *IEEE Transactions on Power Delivery*, Vol. 8, Iss. 2, April 1993.

7 "Power Cable Manual," Southwire Company, Carollton, GA, USA, 3rd Ed. 2005.

8 "Engineering Data for Copper and Aluminum Conductor Electrical Cables, " Bulletin EHB, The Okonite Company, Ramsey, N.J., U.S.A. 2005.

equivalent to the spectrum of a single CFL scaled up to the maximum rated load for a given wire gauge (for 500 kcmil wiring, this would be up to 320A for 60°C rated copper cable[9]). More realistically, a load consisting of multiple, smaller nonlinear loads sharing the circuit needs to be explored. An example would be hundreds to thousands of CFLs installed in a hotel supplied by a three-phase system.

Since physically replicating such a configuration would not be practical, a modeling approach was used. A Monte Carlo simulation was created to model the effect of multiple CFLs on a single load. This approach considers that fact that each CFL contains electrical components whose values will vary randomly within a specified tolerance (for example, resistor values are within ±5% of their rated value and most capacitors ±20%). Therefore, the performance of each CFL will vary slightly. Therefore, the measured current waveform and corresponding frequency spectrum will be a superposition of multiple, slightly varying loads.

Figure 3 shows the simulated spectrum for a 1, 9, and 70 CFLs. The fraction of harmonic content is largest for the single CFL case, and becomes less significant as the number of CFLs increases. As each CFL will be slightly offset in time from one another (in other words, the discontinuous increase in current from each CFL will occur at a slightly different time from the other CFLs). The result is that the measured current waveform will show a softening of the current spikes, which will diminish the magnitude of the higher frequency components. Experimental measurements using different numbers of CFLs sharing a circuit have confirmed the simulation results.

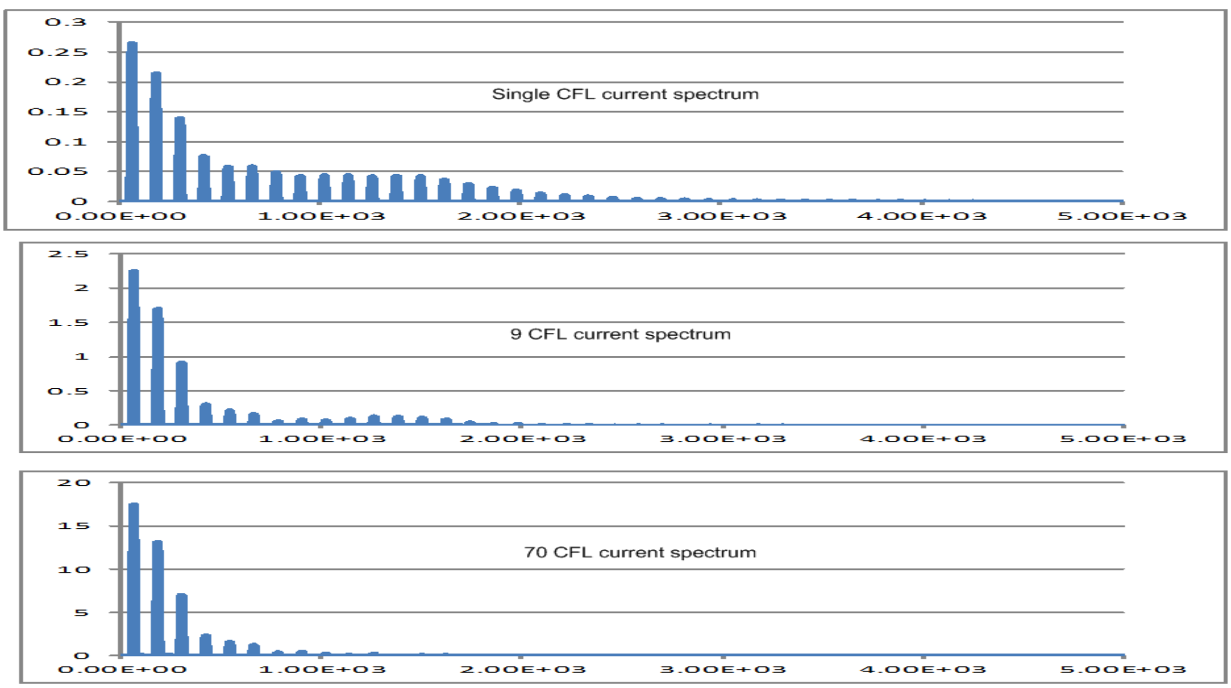

Figure 3. Frequency spectra for a single CFL (Top), 9 CFLs (Middle), and 70 CFLs (Bottom). As the number of CFLs increases, the effect is an overall reduction of harmonic content.

[9] NFPA 70E, *National Electrical Code*, Section 310.15, Table 301.16, 2008 Edition.

These results show that the addition of many nonlinear loads on a circuit tends to *reduce* the fraction of harmonic content on the electrical distribution system, rather than adding to it. Calculating the added heating effect of the wiring due to skin effect heating shows that de-rating less than 5% would be required for 2 AWG if only 9 nonlinear loads were present, and less than 1% once the number of CFLs increases above 70. Considering that the NEC requires no greater than 80% loading for any circuit, it is not expected that the presence of many nonlinear loads, such as replacing hundreds of incandescent bulbs with CFLs, will pose a hazard due to skin effect heating.

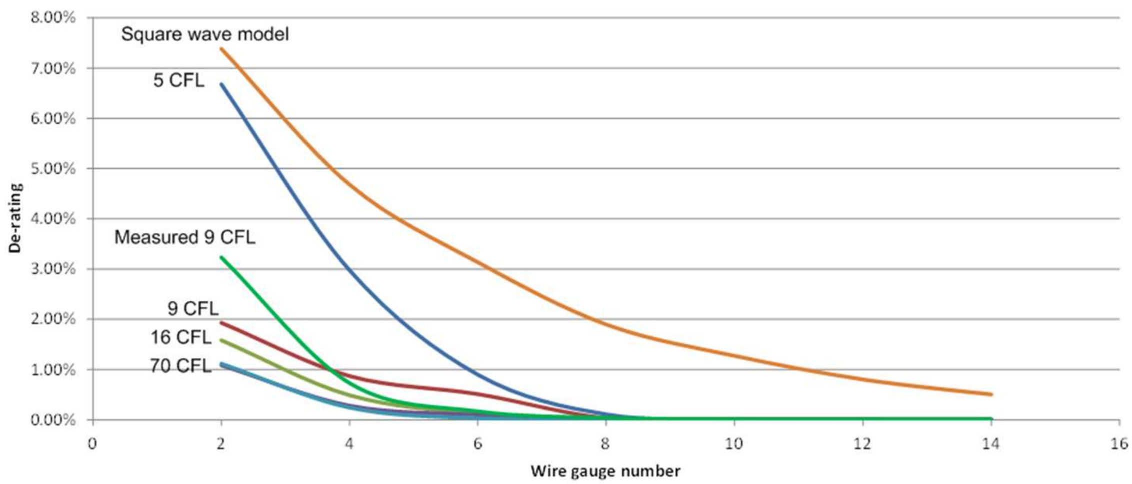

Figure 4. Calculated derating of cable to compensate for skin effect heating. The harmonic de-rating decreases as the number of CFL increases. The 1/6 duty cycle square wave model provides a reference for worst case de-rating.

Effect of CFLs on Transformers and K *Factor*

Harmonic heating also affects transformers, due to the fact that the electrical impedance of an inductor increases with frequency. The amount of harmonic heating a transformer can tolerate is characterized by the *k factor*, which is defined by the following equation:

$$k = \frac{\sum_{h=1}^{34} (i_h h)^2}{\sum_{h=1}^{34} (i_h)^2}$$

Here, i_h is the magnitude of the spectral component at frequency h. Though it is similar to total harmonic distortion (THD), the k factor is more appropriate for evaluating transformer heating as it weights each component based on its corresponding frequency.

Both experimental and simulation work were used to evaluate the effect of k factor with respect to the number of CFLs in a circuit. A representative graph is shown in Figure 5. The results are similar to what was found with the skin effect heating: the superposition of CFL waveforms tends to reduce overall harmonic content. This has the effect of reducing k factor as the number of CFLs increases. In the limit as the number of CFLs becomes large, *k* factor approaches 9. Ref. 5 confirms our result, citing a theoretical maximum *k* factor of 9 for systems with large numbers of nonlinear loads. This *k* factor rating is very common for transformers, and therefore does not suggest a significant safety issue as CFLs and nonlinear loads dominate.

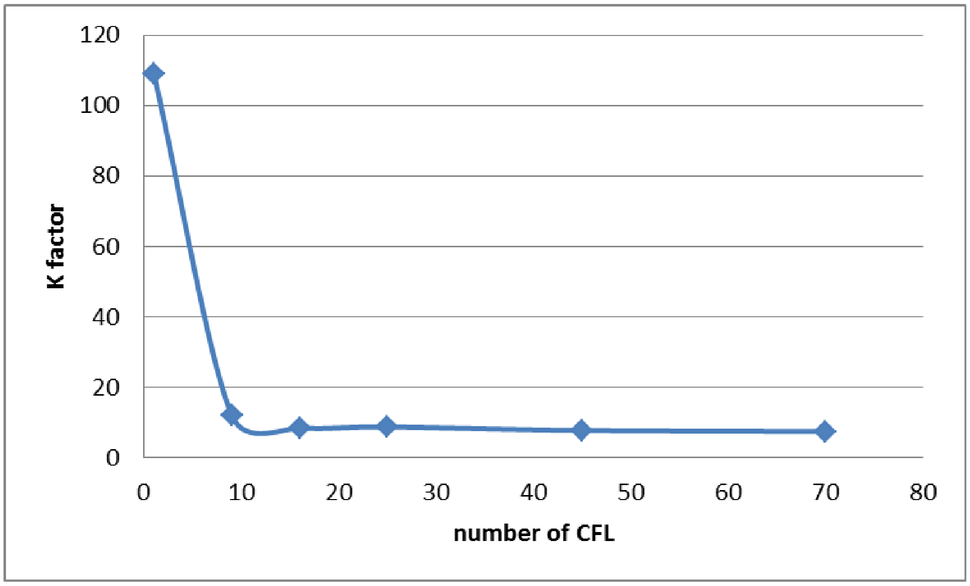

Figure 5. *K* factor data calculated from experimentally measured spectra of CFLs. As can be seen, *k* factor approaches 9 in the limit when the number of CFLs becomes large.

Conclusion

As energy efficiency becomes of increasing importance, incandescent bulbs are slowly being replaced by CFLs and LEDs. This transition has been conducted, until now, without a rigorous investigation into whether placement of CFLs and LEDs into an infrastructure designed for incandescent loads is inherently safe. In this work, the potential hazards of installing CFLs into luminaires intended for incandescent bulbs was evaluated, and showed no significant issues with the practice. The effect of multiple CFLs on the electrical infrastructure was also investigated, and was shown that increasing the number of CFL loads on a circuit has the effect of reducing harmonic heating effects rather than compounding them. Therefore, this study suggests that CFLs will not likely introduce unique fire or electrical safety issues as they replace incandescent lighting. In addition, as CFLs electrically resemble LEDs and other nonlinear loads (such as most modern televisions, computers, and other consumer electronic products), this study suggests that the fundamental change of the nature of electrical loads from a linear to non-linear type is not expected to cause significant fire hazard issues due to harmonic heating. Though other nonlinear loads have very similar spectral behavior with CFLs, we are continuing with experimental and modeling work with a focus on commercial LED and other nonlinear loads to confirm that the behavior resembles the CFL case. Future work activities include investigating the effects of harmonic-generated noise on powerline communications and safety equipment such as GFCIs and AFCIs, as safety considerations from these sources of noise were not evaluated here, and therefore would benefit from additional research on this topic.

Author Biographies

Paul W. Brazis, Jr. is a Research Manager at Underwriters Laboratories (Northbrook, IL, USA). He has a background in electrical and thermal characterization, electronic materials, and device physics, receiving his BS, MS, and PhD in Electrical Engineering in 1995, 1997, and 2000 respectively, all from Northwestern University. Paul joined UL in 2008 from Motorola, Inc. and currently leads the Electrical Hazards research team within UL Corporate Research. This team has a focus in various aspects of electrical safety, including ac and dc arc fault phenomena and detection, component degradation and ignition, harmonics, novel lighting, wireless transmission, and photovoltaic safety.

Fan He is a Research Engineer at Underwriters Laboratories (Northbrook, IL, USA). He received his PhD in physics from University of Cincinnati in 1992, and has a background in signal processing, mathematical modeling and circuit simulation. Fan joined UL in 2010 from Motorola, Inc. and is conducting research activities in the effects of harmonics on electrical infrastructure, arcing ignition of materials, and aging effects of residential cabling.