Compact Fluorescent Lamps and Their Effect on Power Quality and Application Guidelines

Monte K. Richard[1], *Member, IEEE and* P.K. Sen[2], *Sr. Member, IEEE*

***Abstract*- The compact florescent lamp (CFL) is becoming an increasingly popular light source for households replacing the commonly used incandescent lamps. CFLs have advantages and disadvantages; among those advantages are cost savings, energy reduction, increased efficacy, and longer life expectancy. Appearance, poor power factor and harmonic impact on distribution systems are some of their disadvantages. This paper discusses the various application issues related to the CFL's.**

***Index Terms*- Compact Fluorescent Lamps, Power Quality, Harmonics, Energy Savings.**

I. INTRODUCTION

The compact fluorescent lamp (or CFL) is being used more and more in the residential homes. Advertised as an energy efficient lighting solution and driven by the climate change and environmental issues, many households have begun phasing out their incandescent lamps and replacing them with a twisted, tubular, opaque lamp called a CFL. Governments are helping the growth of this new technology and the new energy bill of 2005 and 2007 will phase out most of the common incandescent lamps used today and replace them with energy efficient CFLs. This efficiency comes at a cost on power quality. The CFL electronic ballast creates significant harmonic distortion that lead to power quality issues in distribution systems. This paper compares the CFL and the incandescent lamp and discusses the CFL in terms of its efficiency, cost savings, harmonic distortion, the impact of government regulations on lighting, and their impact on power distribution systems.

II. COMPACT FLUORESCENT LAMP DEFINED

The central element in a fluorescent lamp is a sealed glass tube. The tube contains a small amount of mercury and an inert gas, typically argon that is kept under low pressure. The inner surface of the tube contains a phosphorous powder coating [1]. The tube has two electrodes wired in an electrical circuit that includes an electronic or electromagnetic ballast. When the lamp is turned on electrons migrate through the gas in the tube between the electrodes, and turning the liquid mercury into a gas. As electrons and charged atoms move through the tube, some of them will collide with the gaseous mercury atoms. The collisions excite the atoms, moving them to higher energy levels. As the atoms return to their original energy level, a light photon is released. The wavelength of the photons released is in the ultraviolet (UV) range of the light spectrum. The phosphor coating on the tube converts the UV light to visible light. As a result of the converted wavelength the light output appears to be blue or 'cool' in appearance [2].

Fluorescent lamp efficacies range from 45-90 lumens/W. The low surface brightness and lower heat generation make them ideal for offices, schools, libraries and other similar locations where inhabitant's visual and thermal comfort is very important.

Fluorescent lamp operation is optimized at approximately 25^0C. Figure 1[5] plots the relative lumen output versus the ambient temperature. As the ambient temperature changes, the lumen output will decrease approximately 10% for every 10^0C deviation from the 25^0C value.

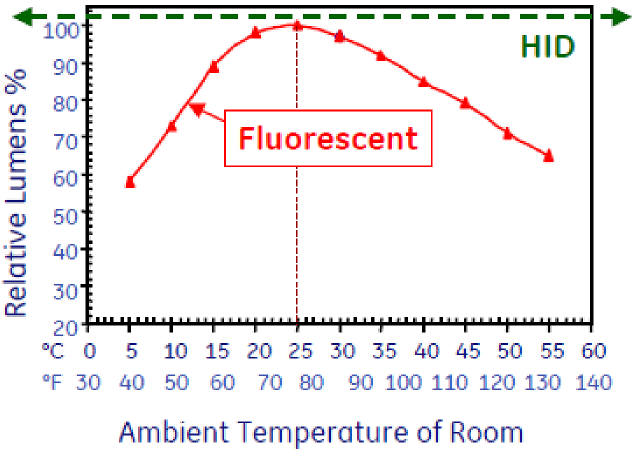

Fig. 1: Temperature Effects on Fluorescent Lamps [5]

The compact fluorescent lamp was first introduced into the marketplace in the early 1980s. Figure 2 depicts a typical medium base internally ballasted CFL. The CFL, simply, is a compact version of the traditional tubular fluorescent lamp typically found in 4' and 8' lengths. Typical power input to CFLs is usually less than 25W.

The lumen output of a 15W CFL compares closely to that of a 60W incandescent lamp. CFLs advertise significant cost savings, energy efficiency and long life [3]. They are commonly used residentially to replace medium base incandescent lamps and industrially to replace low and high bay high intensity discharge (HID) lamps.

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[1] Monte Richard is with Carollo Engineers, Littleton, CO 80122, USA, email: mrichard@carollo.com.

[2] P.K. Sen is with Colorado School of Mines, Golden, CO 80401, USA, email: psen@mines.edu.

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Fig. 2: Internally Ballasted Compact Fluorescent Lamp [1]

III. GOVERNMENT REGULATIONS AND STANDARDS

Many power utilities have created a program called Demand Side Management (DSM), allowing them to offer rebates for conversion to energy efficient devices and lamps. For example, in some cases, a $5 to $10 refund may be offered for each lamp replaced with a CFL [6]. Much of the promotion for conversion to CFLs is carried out by utilities' DSM programs. Some utility DSM programs only offer rebates for electronic ballasts with less than 20% Total Harmonic Distortion (THD). However, most DSM programs currently make no requirement for limiting harmonic distortion.

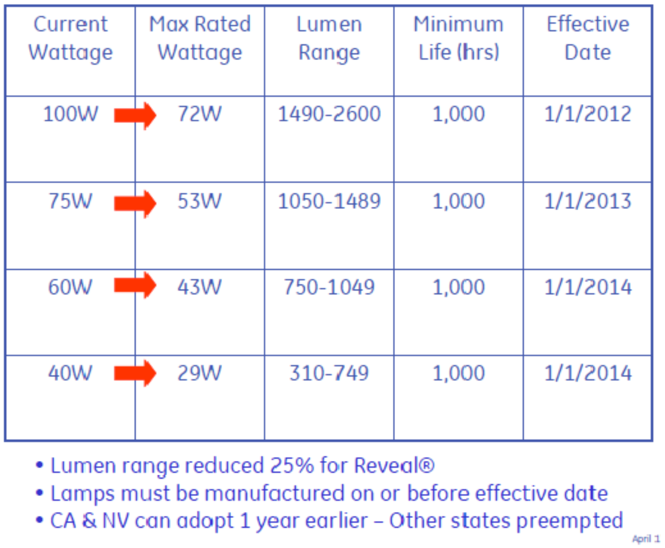
The federal government has also taken measures to promote the energy efficient lighting. For instance, the Energy Policy Act of 2005 [EPAct] offered tax credits in 2006-2007 for energy efficient lighting systems. Qualification was based on the reduction of lighting densities (W/ft^2).

Further, the Energy Independence and Security Act of 2007 (2007 Federal Energy Bill - Public Law 110-140) requires general service "A-line" incandescent lamps including 40W, 60W, 75W and 100W to be phased out starting in 2012. Incandescent lamps will be required to limit their wattage by approximately 25% in order to meet the 2007 bill requirement. Current incandescent lamps will also be discontinued by their manufacturers. Figure 3 shows the wattage reduction required for incandescent lamps. The enactment of this bill will create additional demand for energy efficient CFLs.

An important guideline for harmonic distortion allowed on power systems is given by the IEEE Std. 519-1992 [9]. This standard presents distortion limits for power systems ranging from distribution to transmission voltages. For distribution systems with bus voltages of 69 kV and below, the IEEE-519 Std. recommends that individual voltage harmonic distortion be below 3% and total voltage distortion be below 5% at the point of common coupling.

IV. COST SAVING WITH A COMPACT FLUORESCENT LAMP

Many households have already begun replacing their incandescent lamps with CFLs. As CFL technology has increased in popularity, the price has decreased. A 15W compact fluorescent lamp would have cost nearly $15 ten years ago. Today the same CFL is sold for about $2. The lumen output of a 60W incandescent lamp is close to that of a 15W CFL and costs about $0.60. The lifespan of an incandescent lamp is typically rated at 750 hrs. compared to the CFL value of 8,000 hrs. Assuming the lamps operate for 5 hrs. /day and power cost is $0.07/kWh; the cost comparison is discussed below:



Current Wattage	Max Rated Wattage	Lumen Range	Minimum Life (hrs)	Effective Date
100W →	72W	1490-2600	1,000	1/1/2012
75W →	53W	1050-1489	1,000	1/1/2013
60W →	43W	750-1049	1,000	1/1/2014
40W →	29W	310-749	1,000	1/1/2014

- Lumen range reduced 25% for Reveal®
- Lamps must be manufactured on or before effective date
- CA & NV can adopt 1 year earlier – Other states preempted

April 1

Fig. 3: 2007 Energy Bill and Incandescent Lamps

Incandescent:

- 0.060kW * 5hrs * 365days * $0.07/kWh = $7.67
  Plus the initial lamp and two lamp replacements @ $0.60 each = $1.80
- First year cost for incandescent lamp = $8.87 (2 replaced)
- 5 year cost for incandescent lamp = $45.55 (12 replaced)
- 10 year cost for incandescent lamp = $91.10 (24 replaced)

Compact Fluorescent Lamp:

- 0.015kW * 5hrs * 365days * $0.07/kWh = $1.92
  Plus the initial lamp @ $2.00 and zero lamp replacements = $2.00
- First year cost for CFL lamp = $3.92
- Five year cost for CFL lamp = $13.60 (1 replaced)
- Ten year cost for CFL lamp = $24.20 (2 replaced)

It becomes very obvious that the overall cost is significantly reduced when compared a CFL over an incandescent. As the energy price increases, the difference will be even more and there will be far fewer lamp replacements required.

V. CFL VS. INCANDESCENT AND OTHER LIGHT SOURCES

The fluorescent light source has improved efficacy and has a longer life than incandescent lamps [1]. The use of CFLs in outdoor applications becomes less economical due to efficiency losses at low ambient temperatures. While the efficacy of fluorescent light is significantly higher than an incandescent lamp, these higher efficacies can usually be achieved using high intensity discharge (HID) lamps such as metal halides (MH) and high pressure sodium (HPS). While HIDs are still preferred to compact fluorescents in high bay industrial locations, compact fluorescents are appearing more as replacements for HPS and MH in warehouses where visual comfort is important. CFLs are not optimal in outdoor industrial applications or any application where ambient temperatures vary by more than 10^{0}C from 25^{0}C.

The average lifetime of a CFL is approximately 8,000 hrs, based on a 3 hr/day working period. When they are switched on and off frequently, their lifetime will be reduced. The typical listed life of a common incandescent light is 750 hrs. This means that the average CFL should last about 10 times longer than an incandescent.

A 15W compact fluorescent produces about 950 lumens. A common 60W incandescent lamp produces 1,000 lumens. The relative efficacy (RE) of a compact fluorescent to that of an incandescent is about 4 to 5. This means that, for the same amount of power supplied, a CFL will produce 4 to 5 times more light output than that of an incandescent lamp. Figure 4 compares common incandescent lamps with magnetic (SL) and electronic (PL) ballasted CFLs. Figure 5 shows the average lumens/W of commonly used light sources.

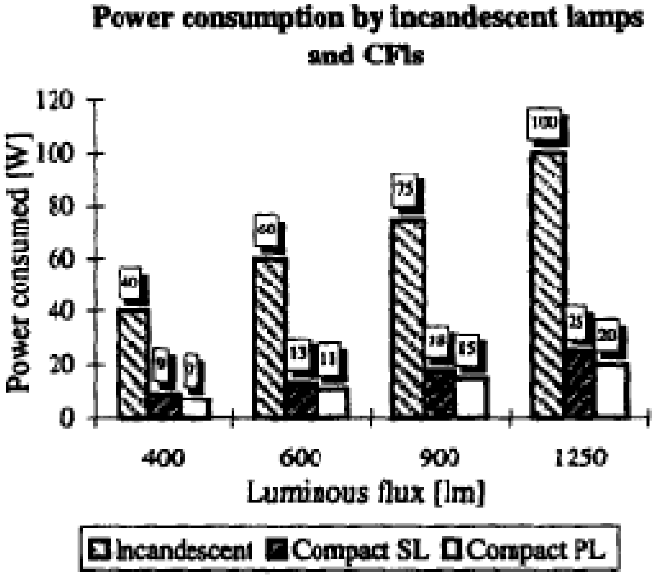


Fig. 4: Lamp power consumption comparison [6]

Domestic lighting constitutes approximately 10% of the load on a distribution system. Figure 6 shows the reduction of domestic energy consumption and the reduction of the total energy consumption when CFL account for different percentages of domestic lighting loads. If CFLs made up 40% of all domestic lighting loads, the reduction of the distribution energy consumption would be 1.6%. In large distribution systems this percentage would represent a very significant amount of saving in power generation.

Color temperature is measured in Kelvin (^{0}K) and it relates to the color appearance of the light. A lamp rated at 3,000^{0}K would appear to be a red color or 'warm tone.' A 5,000^{0}K would have a white color and a 6,500^{0}K would appear to have a blue color or 'cool' tone [2]. Average incandescent lamps have a color temperature below 3,000^{0}K. Average fluorescents have a color temperature above 5,000^{0}K. Most people prefer the 'warm tone' of the incandescent lamp to the 'cool tone' of the fluorescent lamp. CFLs are offered with lower color temperature lamps, for a price. Adjusting the selection of phosphorous used to coat the lamp creates the lower color temperature.

Color Rendering Index (CRI) is a unit of measurement that defines how well colors are rendered by different illumination sources. A low CRI causes colors to appear washed out, a high CRI makes all colors look natural and vibrant. CRI is calculated on a scale from 1-100 where a 100 would represent color rendering equal to that of an incandescent lamp. A general rule of thumb is that the CRI should be at least 80, or some colors will appear unlike their characteristic appearance. An average compact fluorescent CRI is about 85 while an incandescent is 100. While an observer will probably not realize any color issues when using a CFL alone, it will become obvious when a CFL is used in close proximity to an incandescent lamp.

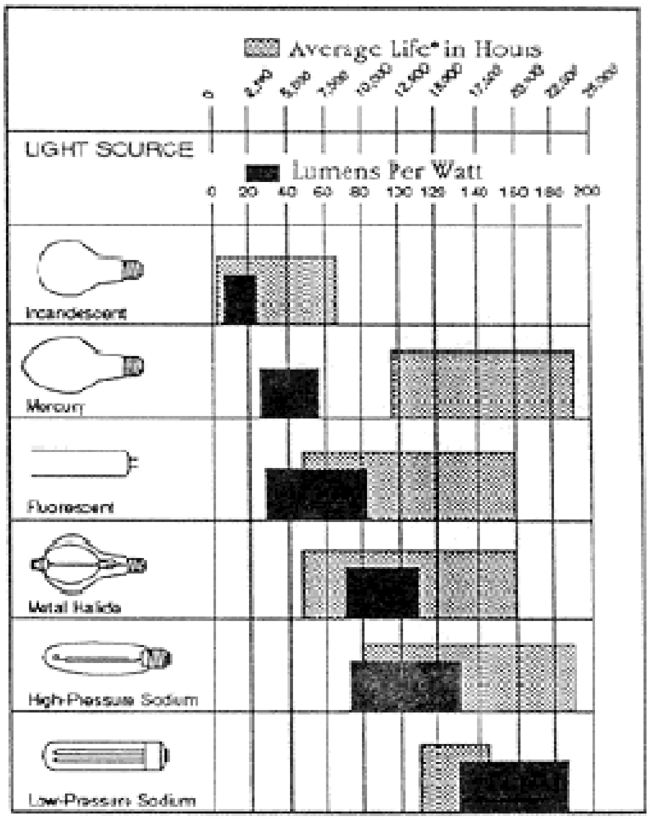


Fig. 5: Average lumens per watt of typical light sources

CFL Penetration	Reduction of domestic energy consumption	Reduction of the total energy consumption
10 %	1 %	0.4 %
20 %	2 %	0.8 %
40 %	4 %	1.6 %

Fig. 6: Energy conservation using CFLs [6]

VI. THE COMPACT FLUORESCENT ELECTRONIC BALLAST

Fluorescent light is created as a result of a gaseous arc. If a fluorescent lamp without a ballast was provided with a constant voltage, the arc would continue to draw current until a catastrophic failure occurred [4]. To solve this problem, a current limiting ballast must be integrated into the circuit to start and operate fluorescent lamps [1].

CFLs are available with two types of ballasts; electromagnetic and electronic. The electromagnetic ballast consists of a wire coil used to limit arc current. Losses in the electromagnetic ballast account for approximately 15 to 25% of the rated lamp power [3]. Electronic ballasts use solid-state electronics to create a high frequency AC voltage to the CFL electrodes. The electronic ballast first converts the supply AC to DC using a full wave rectifier and capacitor. Secondly a high frequency AC output current, between 25 and 40kHz is created from the DC using an inverter. Figure 7 shows an equivalent circuit of the CFL electronic ballast.

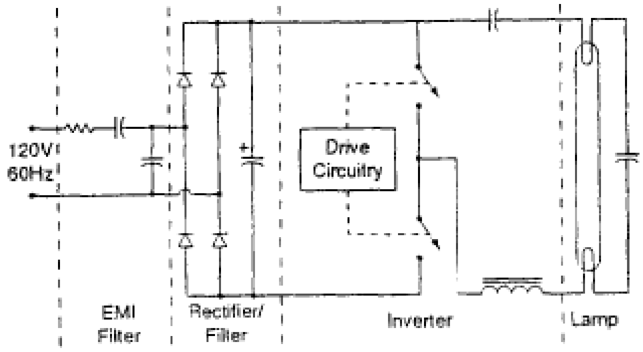


Fig. 7: Equivalent circuit for a fluorescent electronic ballast [3]

Modern day CFLs use an electronic ballast. The electronic ballast operates lamps more efficiently, extends the lamp life, and produces 10-15% more light output. The high frequency operation of the ballast eliminates the hum and flicker seen with electromagnetic ballasts [2].

The main disadvantages of the electronic ballast are the low power factor, usually 0.5 (lag), and high current harmonic distortion.

VII. CFL HARMONIC CONTENT

Large current harmonic distortion is inherent to CFL electronic ballasts [3] and this is the primary concern when analyzing CFL effects on distribution systems.

Figures 8 and 9 depict the harmonic spectrum resulting from actual measurements of manufacturer samples of CFLs with electronic ballasts. Note the overall harmonic distortion is above 100%. Very high 3rd and 5th harmonic components are present. Distortion is rich in every odd harmonic all the way up to the 15th and 17th harmonic component. The waveform presented in Figure 8 resembles that of a single-phase full wave rectifier [4]. This makes sense considering the electronic ballast of a CFL employs the use of a full wave rectifier. No even harmonics are shown in these figures as CFLs do not inherently produce even harmonics due to their half wave symmetry [7][10].

VIII. CFL IMPACT ON POWER DISTRIBUTION SYSTEMS

The continued promotion of the CFLs in the market place has the potential of causing future harmonic issues with power distribution networks. Studies have shown that domestic lighting accounts for about 10% of electrical energy consumption [6]. Total lighting energy was measured to be approximately 20% of electrical energy consumption. The widespread installation of CFLs should be carefully studied in order to realize the effects on various distribution systems.

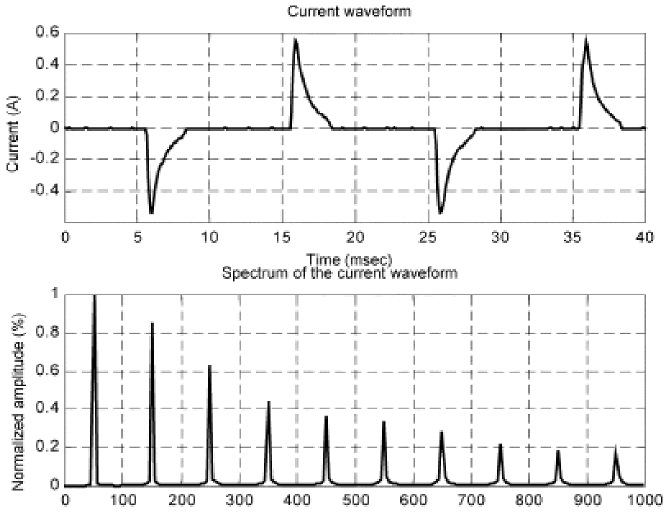


Fig. 8: CFL current waveform and spectrum [7]

NORMALIZED AMPLITUDE (%) OF CFL CURRENT HARMONICS

Harmonic order	20 W	23 W
3	88.9	88.2
5	71.1	69.1
7	48.9	47.4
9	28.9	27.3
11	18.9	18.1
13	16.7	16.1
15	12.6	12.0
17	6.8	6.1
19	2.5	1.7
THD (%)	**130.5**	**127.7**

Fig. 9: Harmonic distribution of CFL current [7]

The negative effects of harmonic distortion on distribution systems are usually seen in the following forms: increased transformer core, hysteresis and winding loss; reduced transformer life; increased service conductor losses; reduced conductor life; and utility loss of revenue due to inaccurate measurement of power factor [3]. These negative affects lead to additional money being spent by utilities on additional fuel, maintenance, and component replacement. Figure 10 shows the expected life of a transformer when operating harmonic rich demand loads. Significant loss of life is seen when operating a demand current rich in high frequencies such as those created by CFLs.

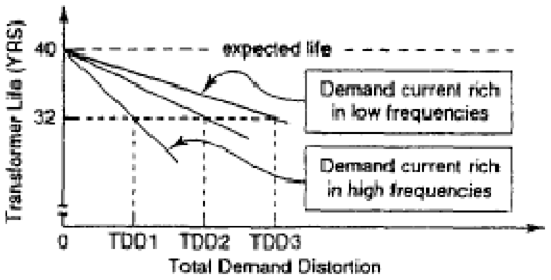


Fig. 10: Transformer loss of life with harmonic loads [3].

The impact of CFLs on a distribution system varies with the selected distribution system. CFL impact will differently effect a strong versus a weak bus. The overall effect on the system will have to do with the harmonic spectrum of the particular supply waveform. The impacts of CFLs are also a function of the distribution feeder impedance. Sprawling distribution system with low impedance will see a larger effect from CFL harmonics. Distribution systems supplied by photovoltaic (PV) or wind generation will also see significant impact [11]. Systems with dense loads and a 'stiff bus' system will see less of an effect [6]. Several research projects have been performed on various distribution systems in order to get a better picture of the effect of non-linearity and CFL loads. Evaluation of the impacts requires detailed simulation of both the distribution system and the CFL itself.

CFLs will also interact with the existing harmonic loads on a distribution system. The output current waveform of a CFL is very similar to the truncated sine output waveform of a PC, and color TV. Therefore, the harmonics generated by the CFL tend to add to existing non-linear loads rather than cancel them out [13].

A. Arki Distribution System Experiment [7]

A study was conducted on a small electrical photovoltaic (PV) distribution system for Arki, a small Greek island of the Aegean Sea [7]. The network consists of loads, linear and nonlinear, supplied from a 25kW autonomous PV power station. The distribution system was simulated and then analyzed under three loading scenarios. The purpose was to find the harmonic impact of replacing incandescent lamps with CFLs under various PV system loading. Allowable voltage THD on the Arki power distribution system was determined to be 8%. This is more lenient than the accepted IEEE-519 limit of 5%.

The measured load profile for the system was approximately 50% lighting and 50% other power consuming appliances. Field-testing showed that the actual distribution system THD ranged from 1.85 to 5.30% while load demand was 8.5kW, or roughly a third loaded.

A simulation of the Arki power distribution system was created. The baseline simulation modeled the distribution system with a THD of 3.14%. When the incandescent lighting loads were replaced with CFLs the THD increased substantially. When the system was loaded; 30% the maximum THD was measured at 10.15%, 60% the maximum THD was measured at 22.2% and 90% the maximum THD was measured at 34%. In all three loading scenarios the THD exceeded the allowable limit of 8%. Of the 42 nodes on the distribution system almost every node exceeded the 8% limit at 60% and 90% loading. Based on the Arki testing and simulation, conclusions can be drawn that a weak distribution system with considerable lighting loads should take strong precautions when allowing CFL replacement of incandescent lamps.

B. 10kVA Building Distribution System Simulation [8]

A simulation was run on a building distribution system where total initial load was 100kVA at 0.85 lagging power factor [8]. In the first simulation scenario, 50% of the demand load consisted of incandescent lighting with unity power factor, and zero harmonic contribution. In a second simulation scenario, the incandescent lighting was replaced with CFLs of a Relative Efficacy (RE) four times that of the incandescent lamps. The CFLs were modeled with a 0.6 lagging power factor and 115% harmonic distortion.

When the CFLs were all installed they comprised 26.3% of the building load. This is a considerable reduction in lighting load, considering the incandescent lamps required 50% building demand for the same light output. However, the system power factor was reduced by 24.0% and the voltage distortion increased by 4.4%.

Figure 11 shows the expected voltage distortion as the percentage of harmonic load is increased on the system. For a CFL with 115% THD, as used in the simulation, to exceed IEEE-519 it must comprise 30% of the total system load. For a CFL with 55% THD to exceed IEEE-519 it must comprise nearly 50% of the total system load.

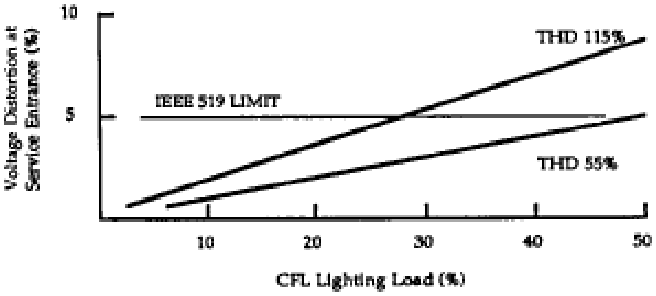


Fig. 11: Voltage distortion vs. CFL loading [8]

Based on the building simulation, conclusions can be drawn that as long as CFL loads comprises less than 30% of the system load, the voltage distortion should fall within the limits of the Std. IEEE-519.

C. Melbourne System Simulation [6]

A simulation was run for a domestic load distribution system in Melbourne, Australia, modeling an 80% loaded, 22kV supply feeder [6]. The THD level of the system was measured to be 3.5% before any CFLs were added to the system. With the addition of the CFLs the THD increased to nearly 5%. When reactive power compensation via capacitors was attempted on the supply feeders the THD jumped to 10%. Based on the Melbourne system simulation, conclusions can be drawn that the switching of power factor capacitors can strongly affect the harmonic impact of CFLs a system.

D. 15kV Feeder System Modeling [13]

Three actual 15kV overhead class feeders with capacity not to exceed 10MVA were modeled in the Eastern Associates service area [13]. The three feeders supply primarily residential customers. The feeders and loads were simulated based on measured data. Each resident on the feeder was assumed to have 140W in CFL load and 100W in TV loads. The substation voltage was modeled with a slight harmonic distortion of about 1.0%.

Simulation was run for two scenarios: The first, where the CFLs and TV non-linear loads were disconnected. The demand was varied from 1,500 to 10,000kVA. The second scenario connected a constant 470kW in CFL load and 335kW in TV load while varying the demand from 1,500 to 10,000kVA. In both scenarios, power factor correction capacitors were allowed to be automatically switched to maintain a near unity power factor.

The results for each feeder show significant change in THD when the CFL and TV loads are included. In all three distribution feeders many of the nodes were above the IEEE-519 allowed voltage distortion limit. As the loading increased the THD decreased. This would have been expected since the non-linear loads were kept constant. It is important to note that each feeder system responded differently to the added non-linear load. The topology, feeder length, impedance and location and size of the correction capacitors all played a factor in how much non-linear loading the feeders could handle. Figure 12 shows the results of THD with and without CFLs for one of the feeders simulated.

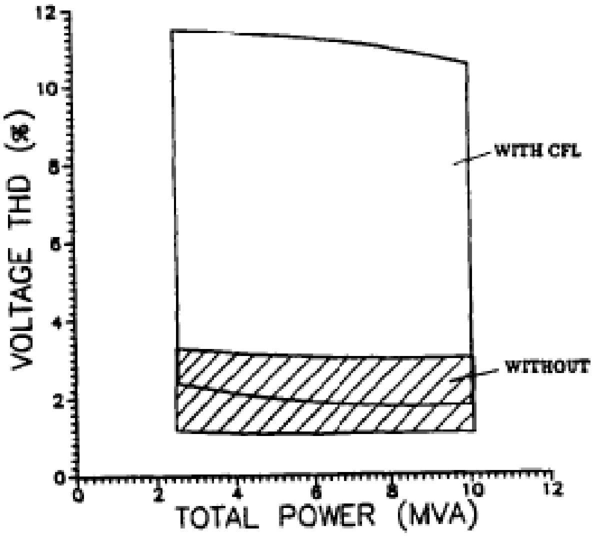


Fig. 12: Simulated effects of CFLs on an existing 22kV feeder[6]

Based on the feeder simulations, the conclusion can be drawn that even if only two or three CFLs are added per home, the harmonic effects may be significant enough to cause voltage distortions greater than that allowed by the Std. IEEE-519.

IX. CORRECTION FOR CFLS

Due to the high harmonic currents created from using CFLs, transformers must be de-rated or a K-rated transformer should be selected. When a portion of non-linear loads can be segregated and put on a dedicated transformer a K-rated transformer is a good choice. This will not only ensure a longer life out of the transformer but will create harmonic correction due to trapping of the tripling harmonics in the delta portion of the transformer. Where possible, it is advantageous to segregate the non-linear loads and deal with them together, rather than randomly throughout the system.

CFLs create a reduced power factor on the distribution system. Capacitors can be added to correct the power factor of a system. CFLs also increase the total harmonic distortion of a system. The use of a tuned filter will effectively attenuate the harmonic distortion of a particular harmonic. However, it will not reduce the other harmonics present in the spectrum. The CFL harmonic spectrum is rich in a wide variety of harmonics; attenuation of only one harmonic will not significantly reduce the overall THD. Therefore, a wide range of filtering would need to be employed to significantly reduce the harmonic impact. Precaution must be taken because the correction capacitors and filters could create a resonant frequency of another harmonic present in the spectrum [13].

Some CFLs are created with "Star Rating," which means that they have harmonic filtration properties. These CFLs are comparatively unpopular due to their increased cost. As CFLs continue to infiltrate domestic lighting, CFLs with harmonic filtering may become mandatory to limit the harmonic effect on distribution systems.

X. CONCLUSIONS

Compact fluorescent lamps create economic saving for the individual user. While an incandescent lamp may be a more aesthetically pleasing light source, CFLs last longer and are more efficient. Great savings can be achieved when using a CFL over an incandescent lamp over an extended period of time.

Compact fluorescents with internal electronic ballasts create a highly distorted current waveform, typically greater than 100% THD. This distortion has the potential to create issues on overall distribution systems.

It is important to note that compact fluorescent lamps will act differently depending on the distribution system in which they are added. There is no blanket statement that states that all systems will meet IEEE-519 regulations as long as the CFL usage is less than 10% of the load. With a total THD of over 100% there is no doubt that the addition of CFLs will create additional harmonics on just about any system. Several distribution system simulations have been discussed herein, and each one provides us with additional pieces to this puzzle. Power quality impacts of CFLs and non-linear loads must be assessed on a case-by-case basis for each individual distribution system.

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XII. BIOGRAPHY

Monte Richard was born in Denver, CO, on May 4, 1981. He received both BS and MS degrees at the Colorado School of Mines, Golden, CO in 2004 and 2009, respectively.

His employment experience includes Carollo Engineers, and Sturgeon Electric. His special fields of interest include the design of power and control systems for water and wastewater treatment facilities. He is a Registered Professional Engineer in Colorado.

P.K. Sen (SM'90) received his PhD in EE at the Technical University of Nova Scotia (Dalhousie University), Halifax, Canada. Dr. Sen is currently a professor of Engineering at the Colorado School of Mines, Golden, Colorado and the Site Director for Power Systems Engineering Research Center. Dr. Sen is a Registered Professional Engineer in Colorado. His research interests include application problems in electrical power systems, electrical safety and arc flash hazard, machines, renewable energy and distributed generation and power engineering education.