

Implications of the Large-Scale Deployment of Non-linear Loads

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To cite this article:

Jomo Nkumah Gill, Gururaj Sudhindra Puneekar. Implications of the Large-Scale Deployment of Non-linear Loads. *Journal of Electrical and Electronic Engineering*. Vol. 6, No. 6, 2018, pp. 153-159. doi: 10.11648/j.jeeec.20180606.13

Received: September 9, 2018; **Accepted:** September 26, 2018; **Published:** January 4, 2019

Abstract: Compared to yesteryear, non-linear loads now proliferate in homes, offices and the industrial environment. Non-linear loads now form a major component of the total loading in the typical electrical network. The Compact Fluorescent Lamp is but one example of a non-linear load that inherently produces and injects distorted currents into the electrical power network, which could create adverse consequences if appropriate and adequate harmonic mitigation techniques are not employed. CFLs are now a major component of the luminaires market around the world because consideration is being given worldwide to the phasing out of incandescent lamps. However, there are legitimate concerns over the quality of some CFLs. This paper investigates and compares the quality of some major brands of CFLs, in terms of parameters such as harmonic content, power factor, fundamental power factor, nonactive power, and apparent power. The wider implication of these results is ascertained by investigating the effects large scale installation of CFLs would have on a generalized electrical network. This work shows that CFLs with high harmonic currents increase the requirements of the source and other network components, as well as place a significant strain on them, since they draw a higher current and also consume a higher apparent power and nonactive power than is necessary for power delivery. Also, it is found that voltage harmonic limits can approach or exceed the IEEE limit of 5% as the number of CFLs deployed is increased. This situation is more pronounced if CFLs with higher current harmonic content are installed.

Keywords: Non-linear Loads, Compact Fluorescent Lamps, Harmonics, Power Factor, Power Quality, Total Harmonic Distortion

1. Introduction

Many governments around the world have made a commitment to ban the usage of incandescent lamps (ILs) and completely replace them by other more energy efficient lamps in their jurisdictions within the short to medium term. CFLs are one of the alternatives to ILs that have gained widespread acceptance chiefly because of their relatively low power consumption, while delivering high lumen output. For example, in terms of luminosity, a 5W CFL is equivalent to a 25W IL and a 14W CFL is equivalent to a 75W IL. This implies that large scale CFL use can be especially beneficial for utilities since it can result in peak shaving, increased

system capacity, and significant savings in the medium and long term [1]. The transition from ILs to other types of lamps such as CFLs is also facilitated by the retrofitting into existing sockets for ILs. Another benefit of CFLs is their reputed longer lifetimes than ILs.

However, a major drawback associated with CFL use is that they draw a significantly distorted current, due to an in-built diode bridge rectifier used to aid in the conversion of the incoming 50Hz ac to a much higher frequency of 20-40kHz, which is applied to the lamp tube. Thus, when CFLs are deployed on a large scale in electrical networks, the quality of power therein can be adversely affected. Researchers have shown that CFLs generally have current distortions that approach or are in excess of 100% which,

depending on the particular network configuration and other connected loads, can cause harmonic limits at system buses and Point of Common Couplings (PCCs) to be exceeded [2-13]. This in turn has the potential to cause mal-operation of equipment of connected consumers.

The current work is useful since many countries are considering making the use of more modern lighting systems mandatory in preference to ILs. However, as regards CFLs, it is first imperative that CFLs in the market be analyzed to determine their key performance parameters, inclusive of their harmonic current injections into the electrical network, which in turn can give an indication of the possible consequences if their usage is widespread. An excess of harmonics in the electrical network has a host of negative consequences, inclusive of increased line losses, thermal stresses on equipment, pulsating and reduced torque in motors and generators, and a shortening of equipment life [14]. Overall, high harmonic levels cause the quality of power on electric power networks to be significantly degraded.

The primary aim of this paper is to characterize, compare and evaluate the behavior of a specific type of non-linear load, that is, CFLs. Focus is placed on analyzing the harmonic content of the major brands of such devices. By extension, the possible effects on a representative portion of the electrical network when the CFLs are deployed on a large scale are investigated using MATLAB/Simulink.

2. Methodology

2.1. Testing of CFLs

Nine (9) models of 5W CFLs manufactured in India were purchased and tested for their current harmonic content using the Yokogawa CW240 Power Meter. For verification purposes, the rms currents of the CFLs were also measured using the Rish Multi 18S True Rms Meter. In all cases there was agreement between the rms current readings of the two (2) meters to within 1mA. All the tested CFLs have electronic ballasts and are of the linear, retrofit variety. Their Maximum Retail Prices (MRPs) range from ₹110 to ₹135.

All lamps were tested at a supply voltage of 223.5V rms, 50Hz, with the harmonic distortion in the voltage not exceeding 1.8%. Harmonic current levels up to the 50th order, as indicated by the Power Meter, were used to aid in comparing and evaluating the lamps' performance with the aid of MATLAB.

2.2. Simulations and Modeling

2.2.1. Algorithm for Computation of CFL Parameters

Harmonic levels for the supply voltage and CFL current up to the 50th order were entered into a MATLAB code used for displaying spectral, phase and time-domain plots of voltage and current, as well as computing various performance parameters for the tested CFLs. The algorithm for the MATLAB Code is given below, with formulae as defined in [15-17]. A sampling frequency of 300kHz was used throughout.

- (1) Input measured rms harmonic currents and phase angles for CFL-1.
- (2) Input measured rms harmonic voltages and phase angles for CFL-1.
- (3) Compute rms current using $I_{rms} = \sqrt{\sum_h I_h^2}$.
- (4) Compute rms voltage using $V_{rms} = \sqrt{\sum_h V_h^2}$.
- (5) Compute apparent power using $S = V_{rms} I_{rms}$.
- (6) Compute active power using $P = \sum_h V_h I_h \cos \theta_h$.
- (7) Compute power factor using $PF = P/S$.
- (8) Compute nonactive power using $N = \sqrt{S^2 - P^2}$.
- (9) Compute total harmonic distortion for voltage and current using $THD_{I,V} = \sqrt{(\sum_{h \neq 1} I_h^2)/I_1^2}, \sqrt{(\sum_{h \neq 1} V_h^2)/V_1^2}$.
- (10) Compute distortion power factor using $DPF = 1/\sqrt{1+THD_I^2}$.
- (11) Display performance parameters and graphs of spectral and phase plots, voltage, current, and harmonic components in sinusoidal form.
- (12) Repeat (i) to (xi) for CFL-2 to CFL-9.

Where:

V_1 and I_1 are the rms values of the fundamental components of voltage and current respectively,

V_h and I_h are the rms harmonic components of the voltage and current respectively,

θ_h is the phase angle between the voltage and current for the h^{th} harmonic.

2.2.2. System Model

The wider implication of the harmonic distortions due to the tested CFLs was investigated by using Simulink to model a simplified and generalized electrical network, where a lumped resistance was used to represent parallel-connected thermal or linear loads for all connected consumers. Specifically, an attempt was made to investigate the impact of large scale deployment of the CFLs on a generalized electrical network. Since emphasis is strictly being placed on the system's response due to CFLs, other harmonic-producing loads, such as arcing devices, switch mode power supplies, and variable speed drives, which comprise many electrical networks nowadays, have not been included since this may cause confounding of the results. This implies that the results and conclusions of this study would represent best-case scenarios. The generalized system to be modeled and investigated is shown in Figure 1.

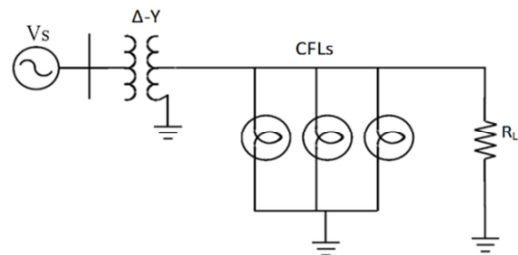


Figure 1. Representative system for investigating the impact of large scale CFL deployment.

Since it allows for a general impression of what can happen in any electrical network using the type of CFLs tested in this study, this procedure was preferred to a Case Study, whose results would only be specific to the system under consideration. The voltage was supplied to the CFLs via the secondary of a 0.2MVA, 11kV/0.433kV, Δ -Y transformer with a rated secondary current of 266.6A and an impedance voltage of 4.11%. The actual voltage used in the model is 223.5V rms at 50Hz since the CFLs were tested for their harmonic content at that voltage level. The line is assumed to be AWG10 aluminium of length 100m and resistance 0.330 Ω . For simplicity, the line is assumed to be a summation of the lengths of the various cables used to supply power to all consumers serviced by the transformer. Each CFL was modeled by current sources at the various harmonic

frequencies with non-zero current amplitudes. The phase angles and power consumption of the CFLs were also accounted for in the model. The impact of the CFLs on the network was investigated by progressively increasing the number of CFLs therein. The interaction and compensation of harmonic levels when various brands of CFLs are employed were also investigated.

3. Results

3.1. CFL Characteristics

The summarized results of the measured CFL currents and the computed parameters for two (2) selected lamps, CFL-1 and CFL-2, are given in Table 1.

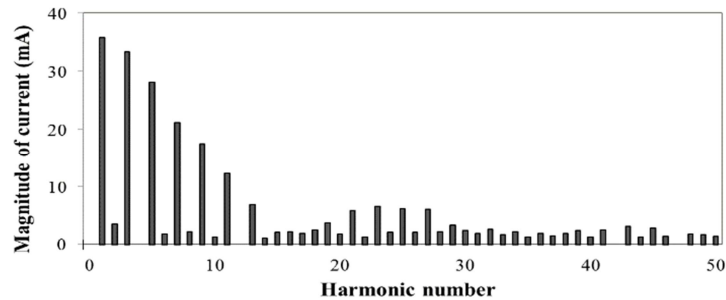
Table 1. Parameters for CFL-1 and CFL-2.

CFL	I_{rms} (mA)	I_1 (mA)	P (W)	S (VA)	N (var)	θ_1 (°)	FPF	PF	THD _i (%)	DPF
CFL - 1	47.459	25.300	5.119	10.558	9.234	25.4	0.903	0.485	157.812	0.535
CFL - 2	23.606	23.300	5.116	5.279	1.302	10.6	0.983	0.969	16.317	0.987

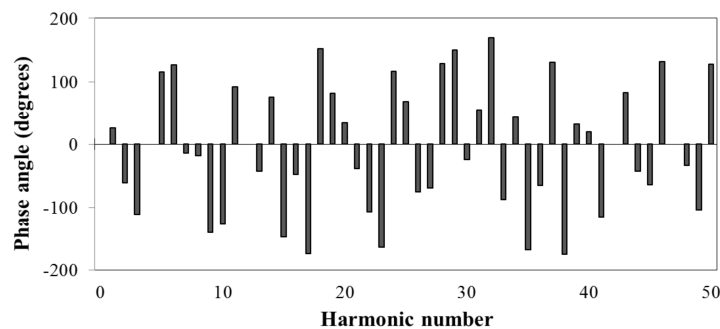
Spectral, phase and time domain plots of these two (2) lamps, which have the highest and lowest current THD values respectively, are shown in Figures 2 and 3. All nine (9) CFLs draw a non-sinusoidal current, with THD_i values varying from 16.32% to 157.81%, of which four (4) are in excess of 100%. All lamps except one (1) have some low-amplitude even harmonics interspersed among the higher-amplitude odd harmonics. Power factors for the lamps varied from 0.49 to 0.97, with an average value of 0.74. High THD_i values correlate with low power factor, with a general tendency for power factors to decrease with increasing harmonic current injections. All lamps with THD_i values in excess of 100% had power factors less than or equal to 0.6.

Fundamental power factors (FPFs) for all lamps were

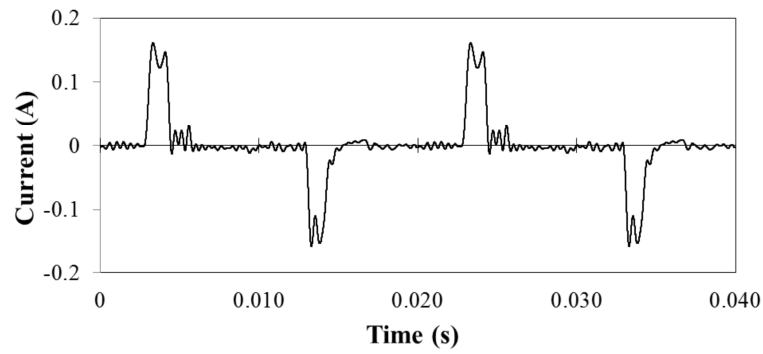
leading and in excess of 0.85, with a maximum value of 0.98 and an average value of 0.93. Since the supply voltage can practically be considered as a pure sinusoid, with THD_v being 1.8% in all cases, the contribution of current harmonics to the power consumed by the CFLs is negligible. More specifically, for all lamps, only the fundamental component I_1 contributes to the active power, with the other current components serving only to increase the requirements of the voltage source. For those lamps with THD_i values in excess of 100%, the unneeded harmonic currents are all in excess of 10mA, with the fundamental component I_1 being much less than the total rms current. With large scale installation of CFLs, especially those with higher harmonic content, the excess current draw and the strain on the voltage source would be considerable.



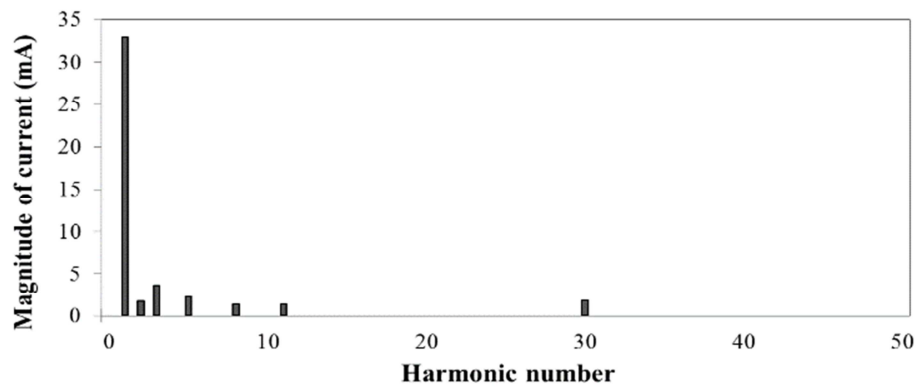
(a)



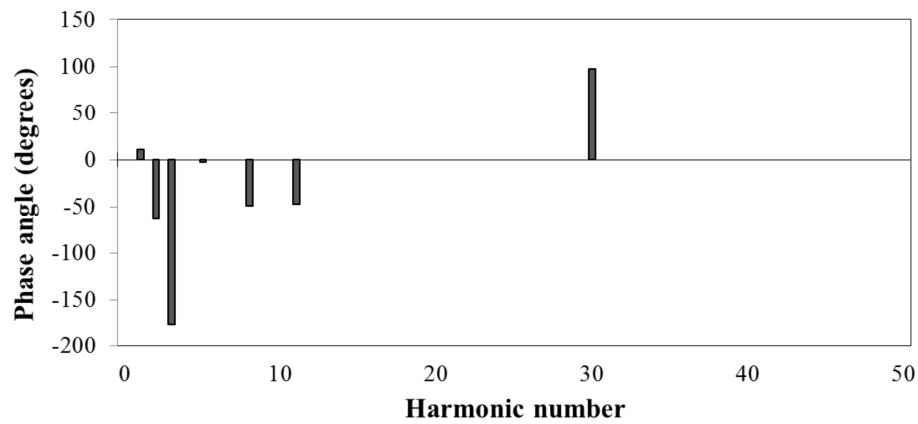
(b)



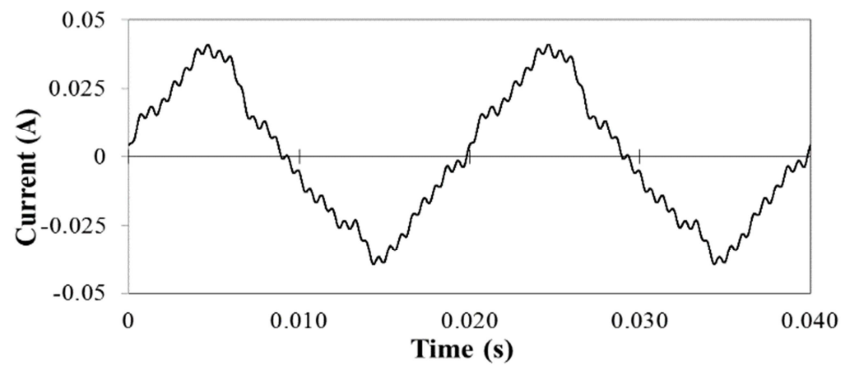
(c)

Figure 2. Plot of CFL-1 current (a) Spectral (b) Phase angle (c) Time domain.

(a)



(b)



(c)

Figure 3. Plot of CFL-2 current (a) Spectral (b) Phase angle (c) Time domain.

A comparison of the results for CFL-1 and CFL-2, as given in Table 1, is instructive in highlighting the drawbacks of a highly non-linear CFL. These two CFLs utilize the same active power (5.12W), but the disparities in the key parameters of rms current (I_{rms}), apparent power (S), nonactive power (N) and power factor (pf) are quite significant. The differences in the values for these parameters are 23.853mA, 5.279VA, 7.932vars, and 0.484 respectively. Hence, extensive use of CFL-1 instead of CFL-2 would result in increased current draw from the supply, which could ultimately lead to transformer overload, increased line losses and shortening of equipment life, if equipment derating or harmonic mitigating techniques are not implemented.

3.2. Effects of CFLs on the Generalized Electrical Network

The effects of progressively increasing the number of CFLs are examined for two cases:

- (1) Case I: CFL-1 only
- (2) Case II: CFLs with different current THD values

The Simulink setup for the investigation is shown in Figure 4, where Z_s is the impedance of the source, R_{line} is the impedance of the line, PCC is the point of common coupling, and R_L represents customers with strictly linear loads.

3.2.1. Case 1: CFL 1 Only

The effect of increasing the number of CFL-1 lamps, which have the highest current THD value of 157.812%, is first investigated. Two cases are examined:

- (1) When CFLs comprise the only load in the system and,
 - (2) When the other parallel loads are a lumped resistance of value 100Ω.
- 1) $RL = \infty$: When CFLs form the only load in the system, and they are progressively increased, there is no change in the THDV values across the network impedances and the THDI values of the current flowing through them. They all remain constant at a value of 157.812%. However, the magnitude of harmonic current injected into the system increases in proportion to the amount of CFLs deployed, which would be a concern when CFLs form a significant portion of the total system loading.
 - 2) $RL=100\Omega$: Progressively increasing the number of CFLs from 50 to 1500, results in an increase in the THDV values across the parallel resistive load. This is shown in Figure 5. The recommended IEEE voltage harmonic limit of 5% is exceeded when approximately 750 CFLs are deployed. The losses on the 100m line due to the harmonic currents vary from 8mW to 0.24W as the number of CFLs varies from 50 to 1500.

3.2.2. Case 2: CFLs with Different THD Values

The effects of two different combinations of CFLs are examined. These are:

- (1) CFL-1 and CFL-2 only
- (2) CFL-1, CFL-2 and CFL-7 only, where CFL-7 has a THD_i value of 49.278%.

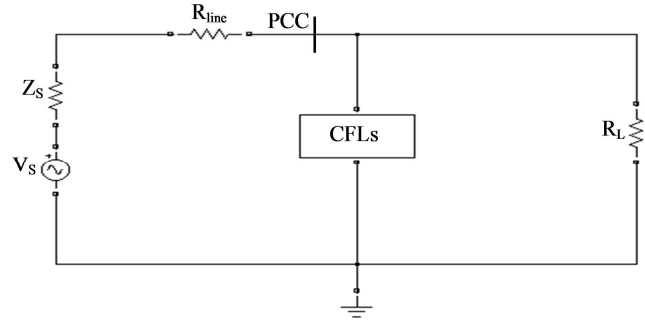


Figure 4. Simulink model of electrical system for investigating the effects of varying numbers and combinations of CFLs.

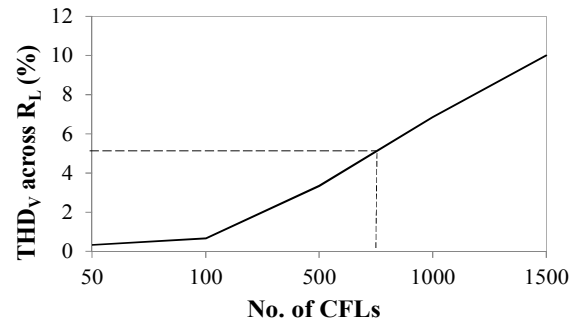


Figure 5. Variation of the harmonic voltage levels across the lumped resistive load R_L with increasing CFL-1.

- 1) $RL = \infty$: When CFL-1 and CFL-2 form the only loads in the system, and they are progressively increased, there is no change in the THDV values across the system impedances and the THDI values of the current flowing through them. They all remain constant at a value of 83.52%. However, the magnitude of harmonic current injected into the system increases in proportion to the amount of CFLs deployed. Similarly, progressively increasing the numbers of CFL-1, CFL-2 and CFL-7 maintains the THDV and THDI values constant, but at a lower value of 63.38%.

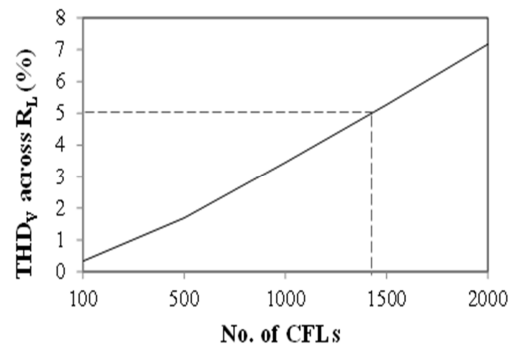


Figure 6. Variation of the harmonic voltage levels across the lumped resistive load R_L with increasing CFL-1 and CFL-9. They are deployed in equal numbers.

- 2) $RL=100\Omega$: Progressively increasing the numbers of CFL-1 and CFL-2 from 100 to 2000, with an equal deployment for both types of lamps on each iteration, results in an increase in the THDV values across the

parallel resistive load from 0.33% to 7.17%. The recommended IEEE voltage harmonic limit of 5% is exceeded when approximately 1450 CFLs, consisting of an equal number of CFL-1 and CFL-2, are deployed (Figure 6). The limit is attained when the CFLs comprise 19.27% of the total possible system loading. The voltage waveform across the load and the PCC when the recommended harmonic voltage limit is just about exceeded is shown in Figure 7. The losses on the 100m line due to the harmonic currents vary from 8mW to 0.16W as the number of CFLs varies from 100 to 2000.

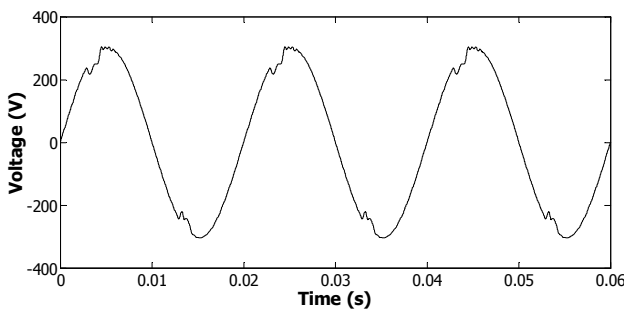


Figure 7. Distorted voltage across R_L when CFL-1 = CFL-2 = 750.

When the numbers of CFL-1, CFL-2 and CFL-7 are progressively increased from 300 to 3000, the harmonic voltage distortion across the lumped resistive load R_L varies from 0.74% to 8.24%. The THD_V limit across R_L is attained when the total number of CFLs is approximately 1950, consisting of 650 each of the three types of CFLs (Figure 8). The CFL loading at this point represents 23.26% of the maximum possible system loading. The voltage waveform when the harmonic voltage at the PCC just about exceeds the recommended limit of 5% is similar to that shown in Figure 7. The losses on the 100m line due to the harmonic currents vary from 16.2mW to 162mW as the number of CFLs varies from 300 to 3000.

4. Discussion

Out of nine (9) tested CFLs, four (4) had a THD_I value exceeding 100%, implying a correspondingly low power factor and highly distorted current waveform. Such lamps draw a higher current than necessary for their rated power and hence shorten the effective capacity of the distribution system. The foregoing is cause for concern since the nine (9) brands considered in this study represent a significant portion of the branded CFLs in the Indian market. It implies that widespread use of CFLs will result in a significant amount of harmonic currents being injected into the electrical network. The lumped resistance R_L considered in this study is representative only of thermal loads connected to the distribution transformer considered as the voltage source in this study. The harmonic currents of the CFLs due to any number of consumers would propagate through the network impedances and cause voltage distortion at the Point of Common Coupling (PCC) and across the linear loads of other consumers. Thus, the distorted voltage at the PCC, due to the CFLs in the system, is also the voltage

across R_L . For simplicity, other harmonic-producing loads which form a significant portion of most electrical networks nowadays have been neglected in this study. Therefore, it is logical to assume that harmonic levels in the simplified network model considered in this study are conservative and much higher voltage distortion levels should be present. This study also shows that harmonic levels due to CFLs with high THD_I values will be offset somewhat by CFLs with much lower THD_I values. Thus, under conditions where sales of the various brands of CFLs are more or less equal, adverse consequences of large scale CFL use would be somewhat lessened. However, if the market share is dominated by CFLs with low power factors, then the quality of power would be affected.

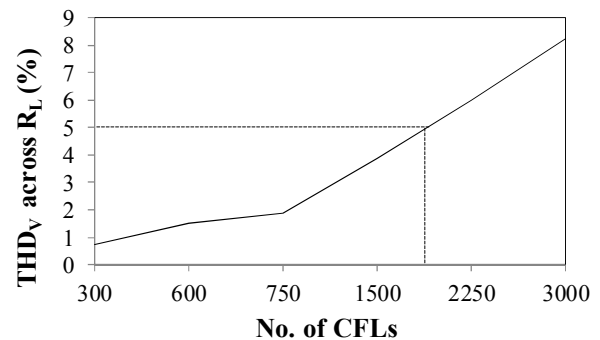


Figure 8. Variation of the harmonic voltage levels across the lumped resistive load R_L when CFL-1, CFL-7 and CFL-9 are increased.

Line losses due to harmonic currents have the potential to approach high levels and are also a source of concern. When a line is much longer than the 100m length used in this study, there would be significantly greater resistance and line losses.

Over the last few years, the number of CFLs manufactured in India has been steadily rising. While the number for other types of lamps, LEDs excepted, has more or less remained constant, the amount of CFLs manufactured has steadily increased from 67 million in 2005 to 453 million in 2013 [18]. And based on the situation in other countries around the world, there is every indication that CFL production in India will continue to rise. Thus, the quality of CFLs manufactured in India, and harmonic levels at key points in the electrical network must be continually monitored so that, if needs be, mitigation strategies can be implemented.

5. Conclusion

The main conclusions of this study are:

- (1) There is a proliferation of highly non-linear CFLs with inadequate or no power factor correction circuitries in the market in India, a situation that can, over time, significantly contribute to high harmonic current levels and degradation of the quality of power in the electrical network.
- (2) Harmonic interaction and mitigation among CFLs, and other non-linear loads as well, in electrical networks may contribute to a reduction of harmonic levels and

their adverse effects.

- (3) Manufacturers need to continue to strive for improvement in the quality of their CFLs since the added cost for incorporating power factor correction circuitry is minimal. As an alternative measure, CFL use should be minimized if not altogether eliminated, and LED use be more widespread.

Acknowledgements

The authors are thankful to the Department of Electrical and Electronics at NITK for supporting this study.

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