# Scenarios for a Large Scale Installation of Compact Fluorescent Lamps: Influence on the Power Quality

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*Abstract:* - The energy efficiency of the compact fluorescent lamps (CFLs) is the main motivation of the promotion policies to replace the tungsten filament bulbs with them. However, their high harmonic content was always a problem for the power quality of the networks, especially the ones with a considerable share of other non linear loads (computers, TVs, electronic devices etc). That problem cannot be neglected in cases of installations with high lighting load (office buildings, educational facilities, hotels etc). In that case the replacement of incandescent lamps by CFLs may cause problems to the power quality. This paper presents an analysis of the low voltage network of a typical electrical installation of a hotel, where lighting is one of the main loads. The complete network is simulated (up to the transformer) using the impedance network model. The CFLs are simulated using their electrical characteristics (active and reactive power, power factor, harmonic content etc) that have been measured in the Laboratory of Photometry of NTUA. The contribution of CFLs to the total load of the network is determined under different scenarios for the scale of replacement of incandescent lamps. For each scenario, the total harmonic distortion (THD) is calculated at each busbar of the network and then it is compared to the respective THD before the replacement. As expected, some scenarios give a non-negligible harmonic distortion although it is always below the upper limits (IEC, IEEE). However, some scenarios (large-scale replacement) may not be realized due to their high harmonic content that will be added to the distortion by other non-linear loads. That means that in case of networks with high lighting loads, the large-scale installation of CFLs should always be studied before replacing the incandescent lamps. Considering the existence of other non-linear loads, the distortion may exceed the maximum allowed values leading to unacceptable power quality.

*Key-Words:* - Harmonics, Power Quality, Compact Fluorescent Lamps

## 1 Introduction

The idea of using efficacious and long-aged fluorescent lamps in those applications that were traditionally the province of inefficacious and short-aged incandescent lamps has resulted in the development of compact fluorescent lamps (CFLs). Compact fluorescent lamps with conventional caps were primarily intended for residential and commercial customers. Lasting much longer and consuming much less energy than incandescent lamps with comparable luminous output, they represented promising new lamp types. An economic analysis also showed an obvious advantage of compact fluorescent lamps compared with incandescent ones [1, 2]. As a part of their energy saving strategy, many power utilities were promoting the use of CFLs, even offering to partially offset their relatively high purchase prices.

The basic problem arising in the mass application of CFLs is the problem with the network voltage distortion that arises due to their distorted currents which contain a high level of harmonic components even at pure sine wave supply voltage. A large number of papers [7-12] have been published dealing with the behaviour of CFLs under various exploitation conditions, i.e. under various voltage distortions and different root mean square (rms) values of the network voltage. CFLs represent the loads with an exceptionally unfavourable current spectral content under various supply conditions, i.e. with very high Total Harmonic Distortion (THD) values.

All these papers pointed to the complexity of the modelling of CFLs working in real conditions, characterized by the non stable rms value of supply voltage and the non stable voltage waveform. Since such a model does not exist yet, the analysis of the voltage distortion in the low voltage electrical installation, presented in the previous section, was based on the assumption that the current spectral content is identical to the maximum permitted (Table 1). Note that the values of current harmonics of the tested samples in some cases [10] exceeded these limits. On the contrary, a small number of analyses were published dealing with the influence of CFLs to power network wherein they are, i.e. trying to establish their maximal presence not leading to the excessive voltage distortion.

In [3] an analysis of the medium voltage network of 13.8kV was made for three different feeders, each of load of 10MVA. The results showed that 3000 to 4000 residential customers in a 10MVA feeder, all of them having two or three CFLs per home, would cause voltage distortion with THD greater than 5%, which is less than the maximum "planning" level of 6.5%, specified by the utilities [4]. During the last few years some international standards for voltage distortion [4], as well as for harmonic current emission [5], were adopted. That is why it is now possible, using some parameters published in them, to make a real estimation of the influence of CFLs to the network voltage distortion. Such an analysis, which, in addition, concerns the low voltage network (with the greatest harmonic components impact), is presented in this paper. An example of a typical hotel electrical installation was analyzed, where a considerable share of the load of CFLs in the total installed load can exist. Note that hotels can be considered as good representatives of commercial customers, which also include, offices, hospitals, department stores, shopping centres.

In general, the voltage distortion problem (its deviation from pure time sine wave function) has become topical with a mass implementation of consumers containing power electronic elements (first, input rectifiers). That is why in the course of the last decade a considerable effort was invested to provide, through the international standards, some recommendations for harmonic distortion limits, being one of the most important power quality factors.

On one hand, the standards protect the customers from the consequences of the bad-quality voltage, by prescribing the maximal permitted values of individual harmonics and of the total harmonic distortion of the supply voltage. Reference [4] contains the data for low, medium, high and ultra high voltage systems.

On the other hand, the standards protect the power utilities (i.e. electric power network), forbidding too high current harmonic components produced by the consumers. IEC Standard [5] provides the limits for the harmonic current emission of the equipment with input current not exceeding 16 A per phase. It is obvious that it was particularly difficult to harmonize the limits for self-ballasted CFLs with electronic gear, omitted in the 1995 edition of this standard. In the valid 2001 standard, the maximal current levels, expressed in mA per lamp wattage (valid for wattages not exceeding 25 W), were adopted. They are provided in Table 1. The third column, showing rms current of the $n^{th}$ harmonic ($I_n$) with respect to rms current of the fundamental one ($I_1$), was determined on the basis of second column and the assumption that the current fundamental harmonic is equal to the ratio of active power and voltage (230V low voltage network).

Note that the standards allow somewhat higher limits for the harmonic current emission [5], under the condition that some particular requests are fulfilled concerning the current change during every period.

Table 1 Maximum permissible harmonic current.

| Harmonic order (n) | per Watt (mA/W) | % of fundamental |
|---|---|---|
| 3 | 3.40 | 78.20 |
| 5 | 1.90 | 43.70 |
| 7 | 1.00 | 23.00 |
| 9 | 0.50 | 11.50 |
| 11 | 0.35 | 8.05 |
| 13 | 0.30 | 6.90 |
| $15 \leq n^* \leq 39$ | 3.85/n | 88.55/n |

*odd harmonics only

## 2 Voltage Harmonics

Voltage harmonic components can be calculated using the impedance network model. All cables, conductors and power transformers can be substituted by equivalent impedances (most often the serial impedance is used). A capacitor is modelled by capacitance between the node corresponding to bus-bars where the capacitor is connected and the reference potential node. The loads (such as resistive loads, induction motors etc) are not shown in the impedance network model because they do not affect considerably the voltage values. However, this is not valid in the cases when the capacitors for fundamental harmonic reactive energy compensation exist. Non-linear loads are most frequently modelled as higher harmonic current generator. Note that the equivalent impedance model is made for each harmonic separately.

The cables, conductors and transformers are modelled as elements with a constant resistance R and constant inductance L. In such a way, for the $n_{th}$ harmonic they are substituted by the impedance:

$$Z_n=R+jn\omega L=R+jn2\pi fL,\ f=50Hz$$

The values of R and L correspond to the direct sequence impedance for the harmonics of order n = 5, 7, 11, 13, 17, 19 etc, while they correspond to zero sequence impedance for the harmonics n = 3, 9, 15 etc. More accurate calculations require to take into account the skin effect, which increases with the increase of the harmonic order. However, this exceeds the needs of the analysis of this paper.

The modelling of a non-linear load by an ideal current generator [6] is based on the assumption that the spectral current content is not affected by the voltage distortion. In the case of some consumers, where very high values of higher harmonic components in the supply voltage could be anticipated, the model of the consumer could be extended by impedance parallel with the ideal current generator.

## 3 Description of the Network

A low-voltage electrical installation of a hotel, representing a typical commercial customer, was analyzed. The nominal voltage of the transformer that supplies the hotel is 20 kV/400V, the nominal power is 1000 kVA and its standard connection is Dyn11. The cross sections and the parameters (resistance and inductance) of the cables and the conductors (internal distribution lines), are shown in Table 2.

Table 2 The low voltage network parameters.

| S ($mm^2$) | R (Ω/km) | X (Ω/km) |
|---|---|---|
| 1.5 | 11.90500 | 0.115 |
| 2.5 | 7.14290 | 0.110 |
| 4.0 | 4.46430 | 0.107 |
| 10.0 | 1.78570 | 0.094 |
| 25.0 | 0.71429 | 0.086 |

Ten cables (25 $mm^2$ each) supply the consumers, which they have equal loads, located in the hotel rooms and corridors (3-phase network). The length of the $10^{th}$ cable is 60 m and the length of the same cross section cables (1, 2, …, 9) is 5 m shorter than the length of the $(+1)^{st}$ cable. Two cables (10 $mm^2$ each) supply the consumers, which they have equal loads, situated in other parts of the hotel (1-phase network). The length of the $1^{st}$ cable is 50 m and the length of the $2^{nd}$ cable is 30 m.

In order to obtain real and reliable data concerning the exact current harmonic content of CFLs so that to use them in the simulation program, many samples of CFLs were tested in the laboratory in order to determine their odd order harmonic spectrum. Such lamps do not produce even order harmonic currents. The nominal power of the CFLs that is widely used in the hotel is 20W. It must be also noticed that the phase difference between the supply voltage waveform and the fundamental current waveform of the tested lamps is negligible. However, the power factor is very low (0.4-0.5) due to the considerable harmonic content of current. The measured values of the current harmonics of this CFL are presented in Table 3. All data from the measurements are properly used as input in the simulation model in order to estimate the influence of CFLs to the network voltage distortion.

Table 3 Harmonics of a 20W CFL

| Harmonic order | Normalized amplitude (%) |
|---|---|
| 3 | 92 |
| 5 | 72 |
| 7 | 53 |
| 9 | 45 |
| 11 | 43 |
| 13 | 40 |
| 15 | 33 |
| 17 | 25 |
| 19 | 21 |
| 21 | 18 |
| **THD** | **158** |

## 4 Simulation

All the electrical characteristics of the network (i.e. transformer, distribution lines and load) have to be accurately simulated in order to obtain reliable results. The simulation of the electric network is performed using the PSCAD v3.0.6 software.

The essential parameters describing the transformer, the cables and the conductors (resistance and inductance) are determined using their values for the fundamental harmonic.

The elements are modelled by serial impedances. The magnetizing current of the transformer was neglected. This is a usual approximation [3], whose adoption introduces a negligible error.

The sources of the harmonics (CFLs) are defined according to the adopted lamp wattage and the current limits given in the second column of Table 1. It is adopted that the currents of the current generators are in phase for every harmonic (the influence of this approximation is also negligible).

The calculation is made under the assumption that except CFLs there no other non-linear loads.

The entire linear load is observed as a load with PF=cosφ=0.85 and its equivalent impedance is connected directly to the transformer low-voltage busbars. This approximation is justified because the impedances of particular linear loads are considerably greater than those of their supplying cables. This impedance is significant in the calculations of the voltage distortion if there exists the fundamental harmonic reactive energy compensation. The load reactance for the $n^{th}$ harmonic is calculated as the load reactance for the fundamental harmonic multiplied by the harmonic order n. Though in the case of rotating electrical machines the adoption of this assumption introduces an error [13], it is usually used in the analyses of this type. The linear load is so selected that the sum of its active power and the total active power of CFLs amounts to 610kW.

A detailed point of view of the proposed simulation is described in Fig. 1.

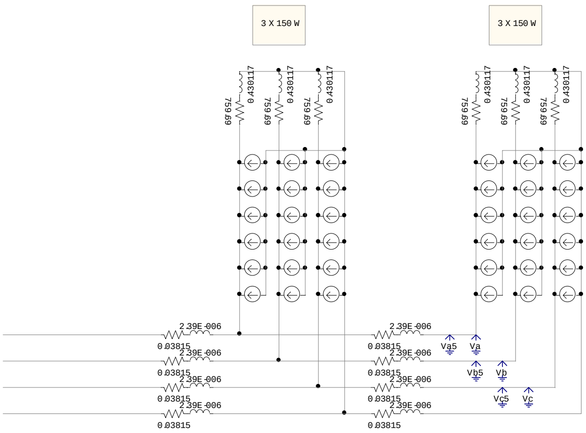


Fig. 1 Part of the electric network (the current sources represent the harmonic content of CFLs)

The electric network of the hotel, after the addition of the harmonic current of CFLs is fully described in Fig. 2 at the end of this paper.

The following four scenarios for the hotel are simulated and examined in this paper.

1st scenario: 25% of 75W incandescent lamps are replaced with 20W CFLs. The total active power of CFLs amounts to 40.67kW. This power corresponds to 4.067% of the rated transformer power.

2nd scenario: 50% of 75W incandescent lamps are replaced with 20W CFLs. The total active power of CFLs amounts to 81.33kW that corresponds to 8.133% of the rated transformer power.

3rd scenario: 75% of 75W incandescent lamps are replaced with 20W CFLs. The total active power of CFLs amounts to 122kW. This power corresponds to 12.2% of the rated transformer power.

4th scenario: 90% of 75W incandescent lamps are replaced with 20W CFLs. The total active power of CFLs amounts to 146.4kW that corresponds to 14.64% of the rated transformer power.

Laboratory measurements showed that the CFLs of 20W have the same maintained luminous flux with the replaced incandescent ones of 75W.

# 5 Results

The calculation results at all electric network buses, where from the consumers are supplied, for all scenarios are given in Tables 4-7. The most significant conclusions derived for all the examined scenarios are also presented and discussed as follows.

Table 4 Voltage THD (%) for the 1st scenario

| Bus | Phase A | Phase B | Phase C |
|---|---|---|---|
| 1 | 1.042 | 1.040 | 1.017 |
| 2 | 1.060 | - | - |
| 3 | 1.102 | 1.100 | 1.077 |
| 4 | 1.110 | 1.108 | 1.086 |
| 5 | 1.111 | 1.109 | 1.087 |
| 6 | 1.063 | - | - |

Table 5 Voltage THD (%) for the 2nd scenario

| Bus | Phase A | Phase B | Phase C |
|---|---|---|---|
| 1 | 2.084 | 2.081 | 2.034 |
| 2 | 2.118 | - | - |
| 3 | 2.197 | 2.193 | 2.147 |
| 4 | 2.212 | 2.208 | 2.162 |
| 5 | 2.214 | 2.210 | 2.164 |
| 6 | 2.122 | - | - |

Table 6 Voltage THD (%) for the 3rd scenario

| Bus | Phase A | Phase B | Phase C |
|---|---|---|---|
| 1 | 3.233 | 3.228 | 3.152 |
| 2 | 3.279 | - | - |
| 3 | 3.396 | 3.390 | 3.316 |
| 4 | 3.416 | 3.410 | 3.335 |
| 5 | 3.419 | 3.413 | 3.339 |
| 6 | 3.284 | - | - |

Table 7 Voltage THD (%) for the 4th scenario

| Bus | Phase A | Phase B | Phase C |
|---|---|---|---|
| 1 | 3.980 | 3.980 | 3.884 |
| 2 | 4.077 | - | - |
| 3 | 4.171 | 4.172 | 4.077 |
| 4 | 4.191 | 4.193 | 4.098 |
| 5 | 4.195 | 4.197 | 4.102 |
| 6 | 4.092 | - | - |

Given that the rest hotel network loads were considered linear one comes to the conclusion that the each time calculated voltage THD factor is the least possibly expected, when replacing incandescent lamps with CFLs. This also means that even in that ideal case (absence of non-linear loads) CFLs do not increase the voltage THD factor up to the acceptable limit of 5% because the circulating currents are very low.

The harmonic distortion problem is a complex one, especially in low-voltage distribution networks. In such cases, every significant change of load synthesis to achieve energy saving must be thoroughly studied. Otherwise problems like unacceptable harmonic distortion may rise.

## 6 Conclusion

This paper considers the problem of voltage harmonic distortion in commercial low-voltage networks with a significant participation of CFLs with electronic gear, which is an important parameter for energy saving strategies. The use of energy saving technologies, i.e. CFLs in order to decrease the power consumption in this category of networks may result in unacceptable distortions in the network line voltage. It is obvious that a limitation, as a percentage of the rated transformer power, is to be taken into account when designing the entire lighting in the buildings of this type. In order to achieve and maintain the desired power quality and performance, appropriate suggestions should be given to the consumers concerning the load quality and quantity that will not increase the THD of line voltage beyond the accepted limits.

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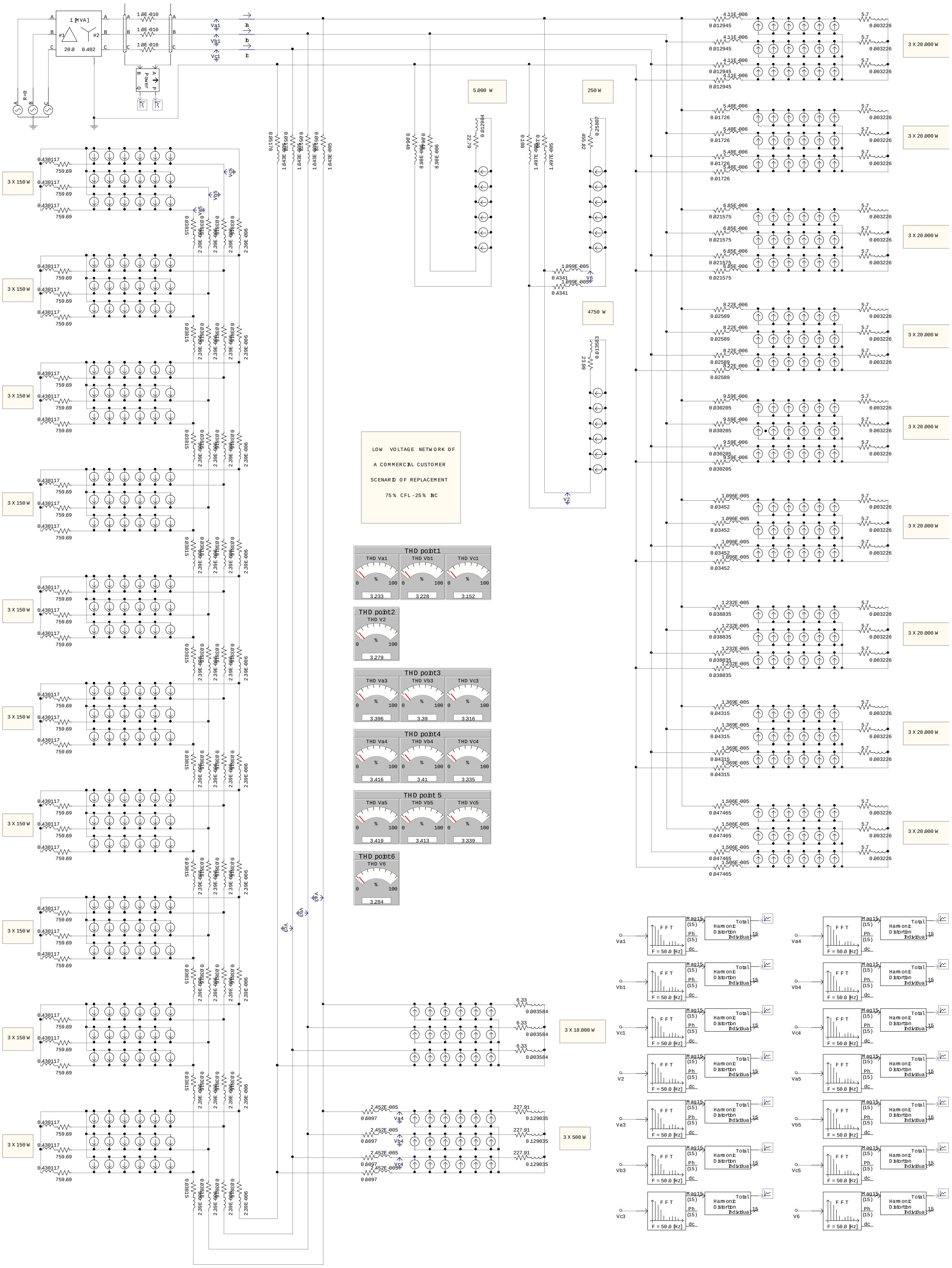

Fig. 2 Simulation of the electric network (the current sources represent the harmonic content of CFLs)