PHISICALLY-BASED MODELLING OF INDUCTION LAMPS: APPLICATION TO THE IMPROVEMENT OF ENERGY EFFICIENCY IN THE LIGHTING SYSTEM OF A UNIVERSITY BUILDING

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INTRODUCTION

To manage efforts in energy efficiency, the Polytechnic University of Cartagena (UPCT) decided in 2003 to develop an ambitious project to reduce energy use intensity and costs during the period 2003-2008. To accomplish this objective in lighting end-use demand -one of the two main electrical uses together with space cooling/heating-, the UPCT joins, in July 2002, the U.E. GreenLight program as a partner. This paper describes the University experience in the second year (2003/04) of partnership in this UE initiative. The objectives were: to manage the demand, to improve the quality of lighting, working and environmental conditions, and reduce significantly energy and O&M expenses. Basically, the work developed in this year is focused in the change of conventional High Intensity Discharge (HID) lighting systems in classrooms (2000 m^2) through the evaluation of advantages and drawbacks of different alternatives. The most promising one, the change to a new technology -165W induction lamps-, will be analyzed in detail in the paper.

ENERGY END-USE EFFICIENCY, ENVIRONMENT AND DEREGULATED ENERGY MARKETS

New technologies and viable control techniques look to achieve an interesting balance between end-use service and energy costs -or savings- in electricity demand. Nowadays there is a considerable potential for improving the energy efficiency in residential and commercial sectors. Several studies in European Union (EU) and USA [1], [2] have estimated that the energy savings potential in the years 2010-2020 range from 10-40%, and also have shown that the electricity savings potential in some sector can reach 40% (institutional buildings and commercial sectors).
Unfortunately, first cost is generally perceived as the main fraction of total end-use costs, which means that, for example, a customer –a University in our case- pays only limited attention to the importance of the energy bill or O&M costs during the life of a certain device. For a lot of customers, there are doubts as to whether the new technologies even save energy, and they are reluctant to spend time and money in energy-efficient projects. The same problem appears in public authorities who have paid in the past more attention to renewable energy sources, sometimes with a little impact but whit larger costs, than to energy efficiency measures or demand response management. In all countries, the consumption per capita is increasing. Specifically, in OCDE countries -with high intensity levels- the energy end-use intensity ratio, ratio between energy consumption (measured in energy units) and economic activity (measured in monetary units at constant prices, for example gross domestic product) is rather stable. In Spain the situation is not the same: since 1990 energy demand is growing continuously partially due to economy growth but sometimes due to the use of technologies with a lower efficiency.
Figure 1 shows the evolution of energy end-use intensity in Spain and in the European Union (EU). It seems clear that energy efficiency should be a primordial concern for public authorities in this decade [1].
On the other hand, the competition in the new deregulated electricity and gas markets has decreased the electricity costs in the last decade for medium and large customers and those energy efficiency improvements have become less profitable. From the authors viewpoint there will be a growing interest on Demand Management and Response in the next years, due to the flexibility and elasticity in the customer demand achieved through load control (short term demand flexibility) and energy efficient policies (medium term). Thus these policies can even be more profitable after the complete deregulation process. In this paper our main objective is to asses a new technology to improve the demand for lighting uses and reduce energy end-use intensity.

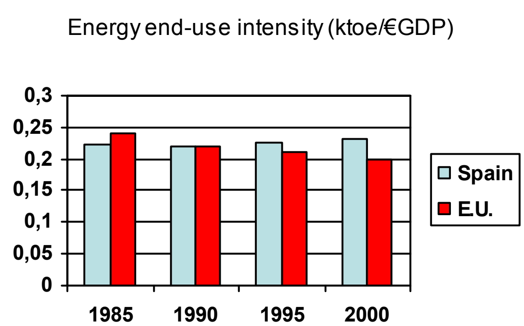

Figure 1. Energy efficiency in Spain vs. EU

The quality and quantity of light are also fundamental factors in this paper because both determine how well users see and work. The amount of energy required for illumination purposes varies for different customers from 20 to 90% of overall demand, according to each geographical area. In UPCT University about 35-45% of annual electrical demand is due to this end-use.
Moreover energy-efficient lighting contributes to solve environmental problems in our societies, as a very useful tool from public authorities to face to increasing pressure to solve

pollution related problems. Without doubt the best energy source to reduce environmental problems is the one that the user does not demand through more efficient devices.

DESCRIPTION OF THE EXISTING LIGHTING SYSTEM

The main building of Higher Technical School of Engineering (ESTII) is part of a series of military works carried out at the military port of Cartagena in the 18th century. It has a surface larger than 35,000 square meters to fulfill the School needs and its basement –the primitive water cistern of military buildings- was restructured and conditioned during the works performed prior to building occupation -in the 90s decade- to be used as classrooms with some daylight possibility. At present, 15 classrooms (2000 square meters, i.e. 1800 students) are available for ETSII academic needs (the luminaries are ceiling mounted and in the upper right corner is visible the skylight, see figure 2).

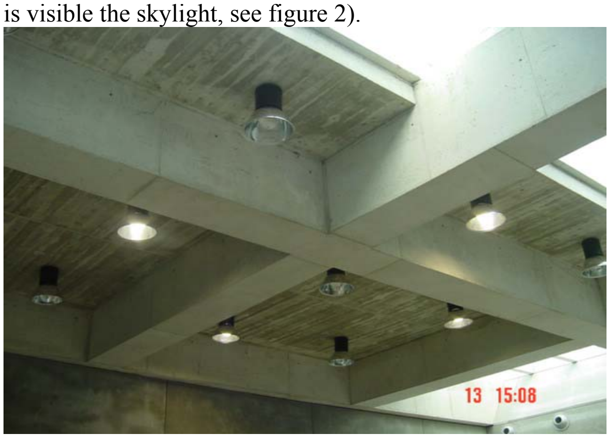

Figure 2. Lamps layout in classroom PS-15.

Unfortunately the architectural solution used for lighting the underground classrooms is quite far from the right solution or end-use needs. The lamps used in there were twenty 150W High Intensity discharge lamps -metal halide- (HID) with magnetic ballast. This lamp technology has three serious drawbacks –for educational needs, of course-:

- Excessive heating of luminaire (i.e. a lower maintenance period)
- Audible noise in the classroom (magnetic ballast and luminaire body), which increases with the age of the lamp and ballast.
- Restarting periods (up to 240 seconds, time that makes very difficult the teaching activity when slides are needed)

The technical alternative to solve the problem here -and besides to achieve an efficient lighting system- appears to be very difficult: the first option is to change to new fluorescent luminaires, the second is the retrofitting of lighting devices with a new technology -induction lamps- or finally the use of electronic ballasts. The first and second alternatives seem -a priori- too expensive (first estimation of the payback period shows a recovery time up to 20 years. Notice all the luminaires in the Old Navy Hospital are only four years old). The third alternative seems the most promising one due to the possibility to use the same luminaire and lamp, but the partnership of ETSII in E.U. GreenLight project and obviously some research interest, moved the authors to take into consideration the second alternative and prove and compare this technology in a test classroom (PB-15).

ADVANTAGES OF THE INDUCTION TECHNOLOGY

Induction lighting is a technology essentially different from that of incandescent lamps or conventional gas-discharge lamps. The technology combines the basic principles of electromagnetic induction and gas discharge to create a lightbulb without filament or electrodes. The elimination of filaments and electrodes results in a remarkable durability –up to 100,000 hours, i.e. about 40 years of operation, based on a mean of 2500 hours/year- . This possibility supposes that this system will outlast four HID lamp changes. Besides Induction has other interesting attributes: long rated life, excellent colour rendering -comparable to that of 800 series T8 lamps-, no colour shift over system lifetime. Moreover they are flicker free, not sensitive to vibration and are stable over a wide range of temperatures. Another advantage of Induction lamps is that some units feature instant restart, hot or cold, and deliver full output of lighting in about 0,1 of a second -an attribute very interesting for our educational purposes-. Unfortunately the first cost of an induction lamp is the highest in illuminating technologies.

These lamps are available in a narrow range of wattages up through 165 watts, and they yield high efficacy uniform illumination. At 70 lumens per watt, they provide about five times the efficacy of conventional incandescent lamps. The lamp selected in our case for the study, a 165-watt lamp, featuring a very ample 12,000 lumens output. These lamps take the shape of traditional incandescent lamps, but they require dedicated fixtures and thus the change of a conventional technology (HID, halogen, incandescent) supposes a non trivial retrofit .
Since 1991 –the first year of commercialization of these lamps-, new applications attest to the great acceptance of induction lighting, specifically for applications with extremely high reliability as a primary requirement and in hard-to-reach locations. Some examples of usual applications –mainly for industrial and outdoor applications- include halls of railway stations and airports, shopping centres, bridges, airports, residential street lighting, advertising light signs, industrial plants and tunnels [3].

RESEARCH PROJECT DEVELOPMENT

The ETSII objective is to achieve energy efficiency while improving:

- The quality of lighting and study work place conditions -to avoid problems of conventional HID lamps in classrooms-.
- The energy efficiency and reduce O&M expenses of the University.

Accordingly to other objectives -E.U. GreenLight project:

- Contribute to reduce greenhouse gases and pollutant compounds (VOC).

- Contribute to reduce EU dependence on external energy sources.
- Offer business opportunities to E.U. industries.

To accomplish these objectives, several tasks are being developed through ETSII research groups in Power Systems:

1.- Monitoring the overall demand and harmonics in main and secondary LV lines.

2.-To evaluate the replacement of magnetic ballasts of HID lamps by electronic ballast in a typical basement classroom (classroom PB-14).

3.-To evaluate the replacement of 150W HID with 165W Induction lamps (classroom PB-15).

4.-To asses benefits and impacts of alternatives 2 and 3 from the viewpoint of electrical LV distribution system and loads.

Some of these works are described in next paragraphs.

Case a: Baseline.

The illuminance and power levels were recorded in two classrooms selected to develop the test experience during three consecutive weekends (15 points of measurement were taken over the student's desk during the morning and the afternoon). Besides, a harmonic analyzer and a PC performed a lot of records during the winter 2003. The results are shown in table I.

TABLE I. Characteristics of the classrooms

Parameter	Classroom	
	PB-14	**PB-15**
Average illuminance level (lux)	850	830
Rated Power (without ballast)	3 kW (1)	3kW (1)
Average power demand (inc. ballast)	3.53 kW	3.64 kW
Average power factor (inc. ballast)	0.791i	0.794i

(1): 20*150W HID lamps

The illuminance level is considerably higher than those recommended in international standards (DIN 5035; ISO8995). According to Maintenance Service of the University, 25% of lamps are replaced every year. This supposes a shorter life (10000 hours) than a priori expected for these HID lamps. The reason for this fact seems to be the higher temperature in the luminaire.

Case b: magnetic ballast change

The withdrawn of magnetic ballast and replacement through an electronic one seems the more suitable alternative to improve lighting efficiency and so to reduce demand. Sixteen lamps have been "retrofitted" with these ballasts (the last file of lamps in the end of PB-14 classroom is switch-off to profit the input of solar light through the skylight).

Case c: induction lamps

In this case, the replacement of HID lamp and ballast for a 165W induction lamp and its electronic high-frequency generator [4] is performed in classroom PB-15. Sixteen lamps have been "retrofitted" with these lamps. The same measurement campaign has been performed in the three cases. To reduce the cost of the field experience the original luminaire has been successfully retrofitted by Maintenance Service staff (see figures 2 and 3)

Figure 2. Change of HID for Bulb Induction system.

Figure 3.Rear side of the original luminaire with HF generator equipment

Results of test field

The change of electronic ballast in PS-14 clearly improves the illuminance levels, but this replacement does not solve two problems: the restarting time (about 180 s) and the noise level (lower than in the case a, but with a higher frequency that causes user rejection).

On the other hand, induction lamps get a lower illuminance level, but without noise and instant restart, while power factor growths up to 0.94i in both cases (b and c). Table II shows a comparison between the performance of systems tested in class PS-14 and PS-15.

TABLE II. Classrooms results

Parameter	Classroom	
	PB-14	**PB-15**
Average illuminance level (lux)	925	550
Rated Power (lamps)	2.4 kW (1)	2.6kW (2)
Average power demand (inc. ballast)	2.00 kW	1.67 kW

Average PF	0.93i	0.94i

(1): 16*150W HID lamps; (2): 16*165W Induction lamps

It was a great surprise -for the research team- to analyze the records of power demand of induction lamps, about a 65% demand than expected (rated power of induction lamps) because this should suppose a nominal demand in the range of 105W/lamps.

To validate these records a new test experience was performed under laboratory conditions through the use of two induction lamps of classroom PS-15.

Several tests with duty cycles to switch ON and OFF the lamp were performed. Illuminance, power and bulb temperature were recorded. The results are shown in figure 4 and prove the validity of our field test.

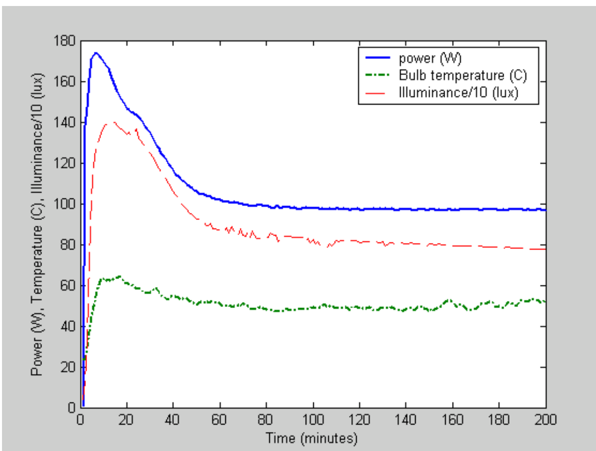

Figure 4. Start transient of an induction lamp

ECONOMICAL EVALUATION OF DIFFERENT ALTERNATIVES

To evaluate costs and benefits of energy efficiency alternatives in both classrooms, it is supposed a conservative usage of 10 hours/day -from 9h to 14h and from 16h to 21h in the afternoon- according to courses schedule.

The assumption of 10 months per year as usage of classrooms is quite accurate, because the building has in summer period some cultural activities (courses) in July and September. This supposes a customer use about 2400 hours/year.

Lighting Costs and Benefits

Equipment. A mean unitary cost of equipment is assumed. The results are presented in table III.

TABLE III. Unitary costs of the equipment

Lighting part	Unitary cost (with VAT)
HID lamp	40-60€
Electronic Ballast (HID)	100-120€
Induction lamp and HF equipment	200-250€

Tariffs. The Spanish electricity market was de-regulated in 1997 (Electric System Act 54/1997) and all users can access to the market prices. The Old Navy Hospital has its specific tariff (a Time of Use, TOU, tariff with six periods along the day. The costs are shown in table IV. For simplicity an average price of 7.368 c€/kWh has been estimated based on use cycles along the year.

TABLE IV. University TOU tariff

Period (*)	1	2	3	4	5	6
Price (c€/kWh)	8.3	7.3	7	6.4	6.5	4.7

(*) According to Royal Spanish Act 2829/1998

Cost analysis of alternatives. A draft analysis has been performed based in equipment, energy and O&M costs for each alternative. The conclusion appears in table V.

TABLE V. Cost of different alternatives (k€)

Cost	Class. PB-14		Class. PB-15	
	Case a	Case b	Case a	Case c
Equipment	1.6	2.56	1.6	3.68
O&M (/year)	0.23	0.04	0.23	0.01
Energy (/year)	0.42	0.24	0.43	0.16

The final result was better than expected for case c and worse for case c (about 30% of electronic ballast presents reliability problems due to heating of luminaire, i.e. higher O&M costs, which supposed the withdraw of electronic ballasts in PB-14). The simple payback for case c is 7,5 years. Moreover, it is expected to reduce this time of payback if additional factors are considered in the analysis, such as lighting quality, EMC problems and the reduction in peak power demand (about 35kW, i.e. from 3% to 5% of overall peak demand). Due to these considerations –mainly user comfort- ETSII performed the retrofit of 12 over 15 classrooms. Scale economies have played with ETSII to reduce lamp costs and payback, so the rest of the dwellings will be changed to induction lamp technologies in 2005.

QUALITY OF SUPPLY

Another important concern is this project is to perform an evaluation of the effect of electronic ballast and induction lamps in the low voltage distribution lines and the transformer center (through the evaluation of K factor). Figure 5 shows the current waveform of an induction lamps during transient and steady-state periods.

transformer works.

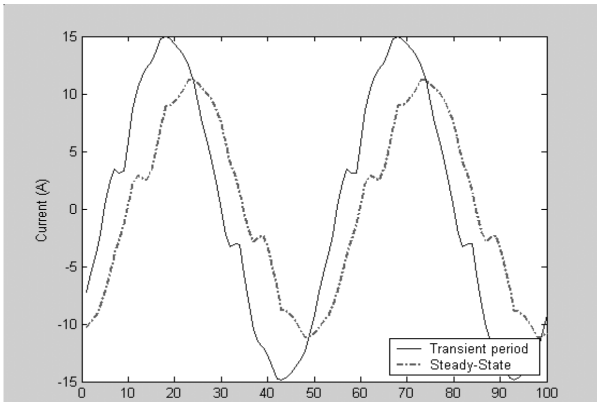

Figure 5. Harmonic current measurements

The tasks performed here are:

a) To develop measurements on the secondary circuits (classrooms PS-14 and PS-15), and transformer secondary to characterize power quality before and after the lighting retrofit.

b) To evaluate the compliance of international standards for harmonic contents.

c) To evaluate the effects of new loads in the transformer through de-rating (K factor).

Several measurements were performed in February 2003. The field experiment was made using an acquisition card system and software -specifically designed- and a harmonic analyzer Fluke41 to obtain K factor in each classroom. The results of these measurements are shown in table VI.

TABLE VI. Harmonic currents (%)

Harmonic (%)	Class. PB-14		Class. PB-15	
	EM(1)	EL(2)	EM(1)	IN(2)
2	0.22	0.11	0.22	0.05
3	15.54	4.55	15.54	2.33
5	6.62	3.01	6.62	0.06
7	10.61	1.63	10.61	0.93
9	12.03	2.69	12.03	2.61
11	1.42	1.38	1.42	0.72

(1): EM: conventional ballast (2): New ballast for each technology

The high harmonic levels introduced by magnetic ballast are under the limits established in EMC standards [9] for sources with rated power over 25W. It can be seen from results of table III that both technologies reduce drastically harmonics levels, specifically induction lamps (current waveform is in this case very close to a sinusoidal wave, see figure 5).

Also some voltage measurements were made in the secondary of the 2*1250 kVA transformer. The voltage distortion is very low in this case (0,35%).

According to ANSI/IEEE C57.110-1986 standard [8] K factor in each classroom, laboratories, offices, library, computer room and halls has been evaluated. The old K factor for case a) (baseline) was 3.58. With new induction lamps and their improvement in harmonic distortion –remember that there are fifteen basement classrooms- and other measures previously presented by authors in [7] –replacement of magnetic ballast, use of CFL lamps- the new K factor for the transformer is 1.25, i.e. the third part of the primitive value. In this way the solution proposed here always benefits the way the transformer works.

CONCLUSIONS AND FUTURE DEVELOPMENTS

It is well known that there are a number of new energy-efficiency process technologies that have application in the major electrical end uses, but are currently not installed or with a limited use. Medium and large customers, and sometimes energy agencies have a number of non-energy related issues that are generally of higher priority than energy-efficiency.

The reason is quite simple because some significant barriers face to energy efficiency improvements: the lack of economic resources at present -utility, distributors, state and national levels-, the difficulty to evaluate additional non energy benefits achieved -environment, quality, reliability-, lower energy costs -due to deregulation processes efficiency has become less profitable-, social education in energy-efficiency and operating and maintenance costs. Markets, regulatory and institutional reforms are needed to increase the reliance on energy efficiency as a resource.

This paper has presented a practical experience –a form to gain the necessary credibility in efficiency policies- with a new technology and a new application not previously described in the bibliography: the use of high power induction lamps for indoor lighting. The simulation and field results show the interest of lighting retrofit technologies, but also the results demonstrate the great potential of the technology. Moreover, student and professors report that the retrofitting of lamps creates an excellent illumination level for the classrooms, helping to the educational activity and avoiding troublesome noise level.

On the other hand the paper shows the possibility to take advantage of existing equipment to reduce project expenses. Power quality problems are also considered and the results are very promising: the use of induction lamps contributes significantly to the harmonics in the customer distribution system in a customer segment where harmonics often cause problems in transformer and electronic equipments.

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REFERENCES

[1] www.iea.org.,2004, Internacional Energy Agency. Information Centre. Energy Efficiency

[2] www.aceee.org.,2004, Proceedings of 2004 ACEEE Summer Study on Energy-Efficiency in Buildings, USA.

[3] B. Cook, 1998, *"High-efficiency lighting in industry and commercial buildings"*, Power Engineering Journal, 12 (5), 197-206.

[4] PHILIPS, 2003, *"Lighting catalogue"*

[5] B. Cook, 2000, *"New developments and future trends in high-efficiency lighting"*, IEEE Power Enginering

Journal, Oct. 00, 207-217.
[6] www.lrc.lpi.edu, National Lighting Product Information Program, 1993-2002, *"Specifier Reports, Lighting Answers"*, Rensselaer Polytechnic Institute, USA.
[7] A. Gabaldón, A. Molina, C. Roldan et al, 2003, *"Rational Use of Energy in a University Building Through Efficient Lighting"*, 17th International Conference on Electricity
Distribution (CIRED 2003), Barcelona, Spain.
[8] ANSI/IEEE standard C57.110-1998, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.
[9]. EN 61000-2 and EN61000-3 Electromagnetic Compatibility (EMC) Standards.