Andrés HONRUBIA[1], Emilio GÓMEZ-LÁZARO[1], Ángel MOLINA-GARCÍA[2]
Antonio VIGUERAS-RODRÍGUEZ[1], Baldomero GONZÁLEZ-SÁNCHEZ[1]

University of Castilla-La Mancha (1), Universidad Politécnica de Cartagena (2)

Assessment of a Novel Energy Efficient System for Fluorescent Lighting Installations

Abstract. *Energy efficiency is one of the most important design requirements for current lighting systems. Retrofitting old buildings with saving energy lighting systems is still unattractive due to economic troubles, such as the high cost of new devices and global rewiring. Though, the advantages offered by wireless sensor networks, propose them as a profitable solution. This paper presents a wireless networked lighting system designed over fluorescent lighting to minimize retrofitting efforts and energy costs. The developed system has been tested over a real deployment of lighting loads. Power consumption is reduced up to 80% of nominal conventional fluorescent tube consumption.*

Streszczenie. *Komputerowe systemy wspomagające projektowanie wymagają od swoich twórców wyboru właściwej: uniwersalnej i odpornej na błędy użytkownika, procedury optymalizacji. Często proponowanym rozwiązaniem jest wykorzystanie w takich systemach algorytmów ewolucyjnych. W tym artykule próbujemy pokazać, że taki wybór nie zawsze jest właściwy. Zastosowanie klasycznego algorytmu deterministycznego prowadzi bowiem do lepszego rozwiązania, które ponadto jest znajdowane znacznie szybciej. Rozważania zostały zilustrowane przykładem systemu wspomagającego projektowanie przepływomierzy elektromagnetycznych.* ***(Wybór procedury optymalizacyjnej dla systemu CAD)***

Keywords: Energy Efficiency, Wireless Sensor Networks, Lighting Systems
Słowa kluczowe: systemy CAD, optymalizacja, algorytmy deterministyczne, algorytmy ewolucyjne

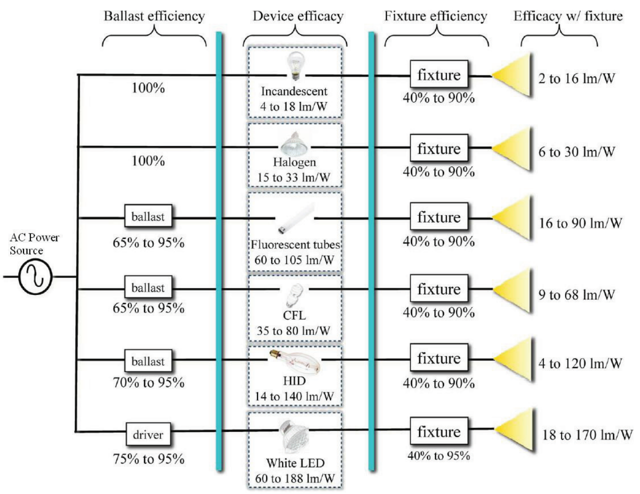

Fig. 1. Efficacy of lighting systems, [2].

Introduction

Nowadays, the contribution of lighting loads to the total electric power demand is around 20% of the world electricity consumption, [1]. Even a higher fraction is found in many developing countries, [2]. Although 25%-40% energy savings could be achieved by using daylight systems, scheduling..., [3], current lighting control technologies are still considered quite luxurious for legacy buildings due to exorbitant retrofitting costs.

The commonly adopted types of lighting devices for electric lighting are incandescent lamps, gas-discharge lamps (fluorescent lamps, compact fluorescent lamps (*CFLs*), Sodium lamps, metal-halide lamps. . .), and solid-state lighting devices (Light–Emitting Diodes *(LEDs)*, high-brightness LEDs, organic LEDs. . .). All lamps, except incandescent and led ones, need high voltage through the electrodes during the starting process to initiate the discharge. Related to energy efficiency, figure 1, [2], reports the range of efficacies for the lighting technologies depicted before. The numbers in the central columns depict the range of efficacies of commercial devices. The numbers in the column on the right report overall system efficacy, that is, the amount of light output from the system per watt of input power source. The numbers on the first and third column represent ballast and fixture efficiencies.

Due to the moderate device efficacy of fluorescent lighting, this is one of the most widespread artificial lighting system, [4]. It can be found in big department stores, supermarkets, office buildings, parking, airports. . . There are two main kind of technologies in fluorescent lighting installations, [4–7]. The first technology is based on traditional fluorescent lighting systems, provided by a set of magnetic ballast and starter (operated at 50 or 60 Hz), which supposes around 75% offices in Europe. The rest of installations are operated by electronic ballasts. These use a switch-mode-type power supply to convert the grid frequency voltage into a higher frequency voltage. This system provides some advantages, such as small volume, light weight, high power factor, high efficiency, dimming operation, lower flicker level and non–audible noise. Nevertheless, some authors point out that the use of a central dimming system for large magnetic-ballast-driven lighting systems can be as energy efficient as electronic ballasts, [7].

The main obstacle of using lighting control systems in legacy buildings with the current technologies is the excessive cost of rewiring, including the addition of the large number of switches and sensors required to achieve the desired level of energy efficiency as well as comfort. Wireless Sensor Networks (WSN) thus have appeared as a new economic solution to elude the main drawbacks of dimmered electronic ballasts, [8–11].

Therefore, the main idea of the present work is the development of a flexible wireless sensor network over fluorescent lighting. The system is designed to vary lamp consumption according to environment parameters, such as daylight. Some authors are focused on developing a new WSN, whereas others are focused on the design of a new electronic ballast. However, the present paper provides a new patented device to control conventional ballasts and a redesigned WSN for lighting applications.

The paper is structured as follows: Firstly the most relevant contributions of WSN to lighting systems are summarized. Then the installation performed covering the design of both WSN and fluorescent controller is described. Later, the preliminary saving parameters achieved by the system are shown. Finally, the conclusions of the paper are given.

Wireless Sensor Networks for Lighting Systems

Wireless sensor networks technologies have enabled many interesting applications in pervasive and ubiquitous computing. However, the emergence of these technologies over some other fields in the last years promises current and future applications for lighting systems. WSN not only takes the cost of wiring out of the equation, but also a quick installation may be achieved over existing lighting facilities. Moreover, in [12] it is shown that the environmental impact of WSN for lighting applications is 18-344 times smaller than conventional lighting systems.

In [9] is reported the implementation of an intelligent light control system for entertainment and media production using WSN. In [10], a wirelessly networked lighting actuation system that minimizes energy consumption and satisfies users' diverse lighting preferences in shared-space office buildings is presented. The results show that relevant energy savings may be achieved dimming the lamps according to users' preferences, although daylight is not taken into account. In [11] an intelligent residential lighting control based on ZigBee wireless sensor networks is designed, although no real experiments are shown.

Therefore, the practical WSN design performed in the present paper close to the novel patented device to control conventional fluorescent lamps, provides several advantages over conventional solutions.

Description of the Experimental Lighting System

The proposed lighting system calculates the optimal combination of the individual lamps. In this way, the entire lighting output is minimized, and hence the energy consumption, while a constant mean illuminance is kept according to both current European Standards, such as [13], and users' requirements. Since power consumption is proportional to light output from the lamp, [14], minimizing the illuminances is equivalent to minimizing energy usage.

Illuminance is measured by each sensor installed next to the luminaire, and the information is sent wirelessly to a microprocessor (μP). This device receives data measured by all the sensors of the room and takes into account the lux level imposed by the user through a designed display. Finally, the μP translate actuation commands to corresponding signals for the lighting regulators to adapt luminaire outputs to user preferences. These preferences are introduced by the users through the display.

Figure 2 shows the framework of the lighting system depicted before. The figure simulates a real example, such as an office lighting system, which is composed of six 4x18 W luminaires commonly used in office buildings. Dashed lines symbolize wireless connections, where red color symbolizes information sent by the sensors to the μP and green color symbolizes actuation commands sent by the μP to the light regulator.

It is important to point out that the size of the set μP and display is quite reduced. In fact, this device has been designed to replace the common swicth of the room where it will be installed. In the upper left side of figure 3 is shown the device over the wall of the room, whereas in the bottom right side of the figure is compared the size of the device versus one hand. Therefore, the user is able to remove the device from the wall at any time, just needing the wall plug when the battery needs to be loaded. The flexibility of the system is thus fully proven.

The display has been designed in order the system to be used by inexperienced users. Figure 4 shows two examples of information offered by the display. The left side of the figure shows an example of system regulated by the lux level imposed by the user. The next parameters are shown:

Fig. 3. μP and display designed.

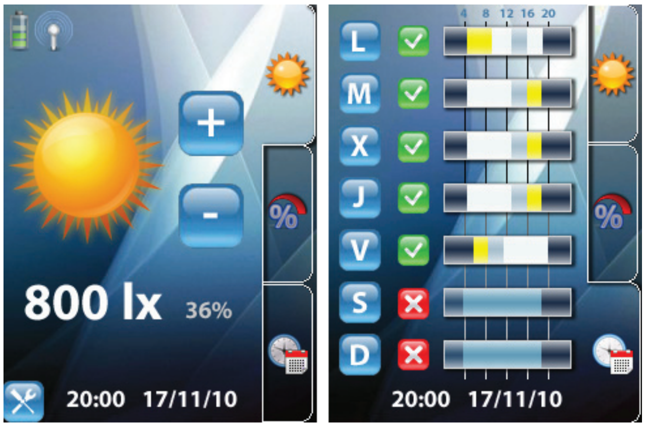

Fig. 4. Example of display.

- Battery: Shows battery status, similar to mobile phones.
- Antenna: This component shows WSN availability. Therefore, the system is able to detect when any communication trouble between sensors appears.
- Buttons $+$ and $-$: To increase and decrease lux level.
- Lux level: Shows the lux level according to sensor measurements.

In the right side of figure 4 is shown the timetable option of the system, which allows schedule hourly turn on cycles according to office working hours.

The developed system depicted before will be tested on a real experiment. Fig. 5 shows the prototype built to perform several well defined experiments. It is composed of the most widespread T8 fluorescent tubes: fifteen luminaires 2x36 W, six luminaires 2x30 W and ten luminaires 2x58 W.

Results

Apart from the intelligent wireless sensor network designed, the aim of the present paper is to depict a recently patented method to control conventional fluorescent lamps. The most important feature of the device is that it can regulate the luminous flux of fluorescent lamps composed of electromagnetic ballast and starter.

Some tests have been performed in order to show energy savings. The tested lamps are two common fluorescent ones of 36 W of nominal power. Both fluorescent lamps were composed by ballast and starter, but one of them was connected through the patented device –for simplicity the lamp without the patented device is called "lamp 1" and the other "lamp 2"–. In the tests were used a luxometer to measure lux level and a *Yokogawa WT1600 Digital Power Meter* to mea-

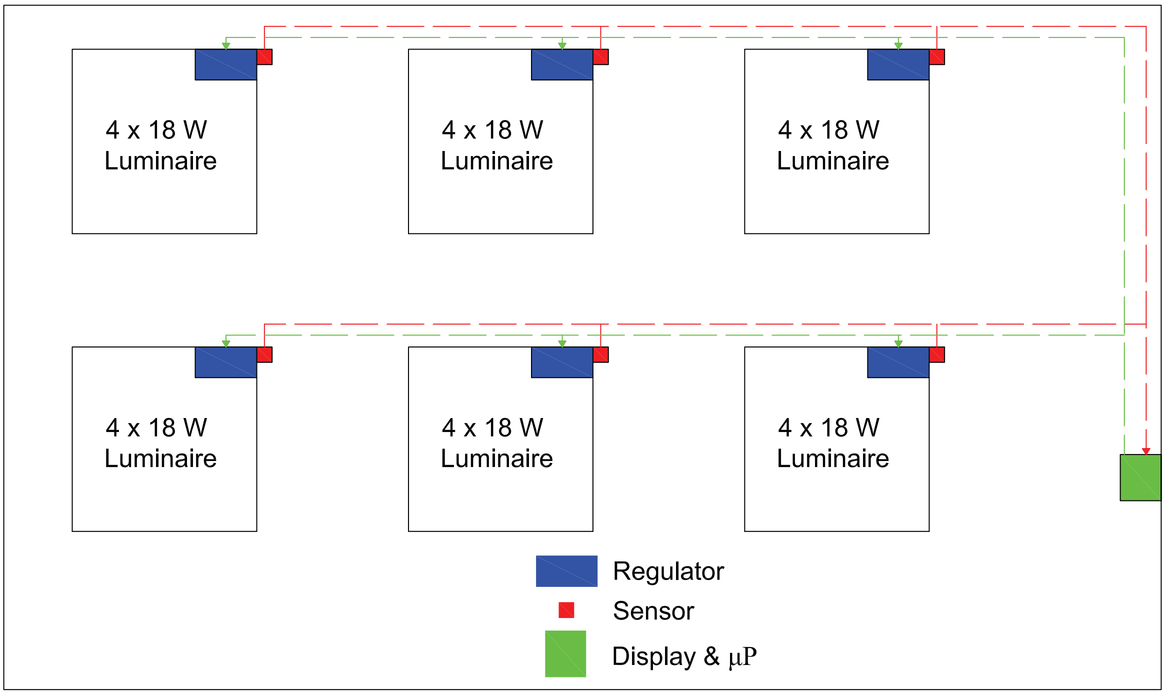

Fig. 2. Description of the lighting system.

Fig. 5. Real test.

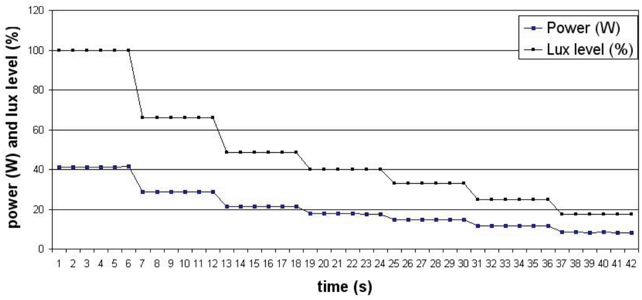

Fig. 6. Power consumption of the fluorescent lamp equipped with the patented device.

sure energy parameters, such as voltage, current and power. The test procedure was to reduce the luminous flux of *lamp 2* until the lamp was off. The power consumption was recorded once per second, whereas the lamp was set to support each regulation stage during six seconds.

Figure 6 shows the test performed. It can be seen that *lamp 2* (the one equipped with the patented device) starts with a consumption of 41.18 W when the lux level is 100%. However the conventional fluorescent lamp nominal consumption is higher: 42.15 W. Therefore, at nominal lux level, the patented device consumes about 1 W less than the conventional lamp.

But, what becomes really important, is the regulation performed because there is no commercial product able to regulate conventional fluorescent lamps. Indeed, table 1 relates power reduction to lux level reduction according to each regulation phase. It can be seen that power reduction goes with lux level reduction.

The last regulation phase shown in table 1 states that the patented device is able to reduce almost 80% conventional fluorescent lamp consumption –what is identical to say that the fluorescent tube is turned on with just 8 W of power–.

Regulation stage	Power reduction (%)	Lux level reduction (%)
1	0	0
2	30.34	33.82
3	48.19	51.47
4	57.05	60.00
5	64.26	67.06
5	71.96	75.29
6	79.79	82.35

Table 1. Power reduction versus lux level reduction.

This regulation thus offers similar properties to electronic ballasts, but these need the electromagnetic ballast and starter to be removed from the installation. However, the patented device adapts to the existing conventional fluorescent lighting system, without replacing any element of the installation.

Conclusions

Regulation of light intensity and power consumption over fluorescent lamps has not been achieved before without using expensive lighting control systems. The main contribution of the present paper was focused on discussing and assessing how the old facilities composed of old fluorescent lamp technologies (75% approx.) can be turned into efficient industries based on the proposed solution, without removing any of the devices previously located in the old installation. Moreover, a novel WSN has been designed, which provides a profitable solution.

According to the tests performed over conventional fluorescent lamps, just connecting the patented device to the existing installation the power consumption is reduced. Though, the most important approach is achieved when conventional fluorescent tubes are regulated depending on environmental parameters, reducing power consumption up to 80%.

The obtained results offer a solution not only to reduce, but also to optimize the power consumptions of lighting facilities, with special care on the most widespread facilities: fluorescent tubes. It thus offers the possibility to regulate and set the lighting level under real needs and current regulations, even on systems that have not been previously regulated, such as fluorescent tubes with traditional ballast and starter. These premises have been applied in a flexible framework, where any kind of existing installation can be also considered, whether jointly or separately for each subsystem that could be thought.

The authors would like to thank "Ministerio de Ciencia e Innovación" (TRA2009-0253-01 and TRA2009-0253-02) for the financial support, and the company Villarrus, S.L. for the technical support.

BIBLIOGRAPHY

[1] R. Yozell-Epstein, "Intelligent lighting system benchmarking," *Masters Report, Department of Mechanical Engineering, UC Berkeley*, 2003.
[2] I. Azevedo, M. Morgan, and F. Morgan, "The transition to solid-state lighting," *Proceedings of the IEEE*, vol. 97, no. 3, pp. 481 –510, 2009.
[3] E. Mills, "Global lighting energy savings potential," *Light and Engineering*, vol. 10, no. 4, 2002.
[4] J.-C. Hsieh and J.-L. Lin, "Novel single-stage self-oscillating dimmable electronic ballast with high power factor correction," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 250 –262, 2011.
[5] J. Alonso, M. Dalla Costa, M. Rico-Secades, J. Cardesin, and J. Garcia, "Investigation of a new control strategy for electronic ballasts based on variable inductor," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 1, pp. 3 – 10, 2008.
[6] C. Nascimento and A. Perin, "High power factor electronic ballast for fluorescent lamps with reduced input filter and low cost of implementation," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 2, pp. 711 –721, 2008.
[7] H.-H. Chung, N.-M. Ho, W. Yan, P. W. Tam, and S. Hui, "Comparison of dimmable electromagnetic and electronic ballast systems–an assessment on energy efficiency and lifetime," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 3145 –3154, 2007.
[8] F. O'Reilly and J. Buckley, "Use of wireless sensor networks for fluorescent lighting control with daylight substitution," *Workshop on Real-World Wireless Sensor Networks*, 2005.
[9] H. Park, J. Burke, and M. Srivastava, "Design and implementation of a wireless sensor network for intelligent light control," *6th International Symposium on Information Processing in Sensor Networks*, 2007.
[10] Y.-J. Wen and A. M. Agogino, "Wireless networked lighting systems for optimizing energy savings and user satisfaction," *Wireless Hive Network Conference*, 2008.
[11] Y. Wang and Z. Wang, "Design of intelligent residential lighting control system based on zigbee wireless sensor network and fuzzy controller," *International Conference on Machine Vision and Human-Machine Interface (MVHI)*, 2010.
[12] M. Dubberley, A. Agogino, and A. Horvath, "Life-cycle assessment of an intelligent lighting system using a distributed wireless mote network," *IEEE International Symposium on Electronics and the Environment*, 2004.
[13] E. 12464-1:2002, "Light and lighting. lighting of work places. indoor work places," 2003.
[14] C. O'Rourke, "Dimming electronic ballasts," *National Lighting Product Information Program*, vol. 7, no. 3, 1999.

Authors:

Ph.D. Student Andrés Honrubia, Ph.D. Emilio Gómez Lázaro, Ph.D. Antonio Vigueras Rodríguez, Ph.D. Baldomero González Sánchez, Renewable Energies Research Institute, Escuela de Ingenieros Industriales de Albacete, University of Castilla La Mancha, Albacete Science & Technology Park, C/Investigación, s/n 02071 Albacete, Spain, email: andres.honrubia@uclm.es, Ph.D. Ángel Molina García, Department of Electrical Engineering, Universidad Politécnica de Cartagena, 30202 Cartagena, Spain.