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Fuzzy logic controller for energy savings in a smart LED lighting system considering lighting comfort and daylight

Jingyu Liu, Wen Zhang*, Xiaodong Chu, Yutian Liu

Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education Shandong University, 17923 Jingshi Road, Jinan 250061, PR China

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ABSTRACT

In commercial buildings, lighting constitutes a large proportion of energy consumption. Saving lighting energy in commercial buildings has aroused great interest among researchers. Achieving energy savings and satisfying lighting comfort are the two primary objectives in designing a lighting system. In this paper, a fuzzy logic controller was designed that considered daylight, movement information and lighting comfort. The DALI protocol was used to communicate the controller with LED luminaires. The simulation results demonstrate that lighting system without control can provide sufficient illumination. The lighting system provides wider controllability to make lighting environment operating at the most energy-saving state. The experimental results show that by using the designed controller, significant lighting energy can be saved. The office where the smart LED lighting system is installed can regulate lighting output automatically based on users' movements and allow users to choose their own lighting preferences.

1. Introduction

Commercial buildings consume more than 30% of the total primary energy [1,2]. Electric lighting is estimated to account for 20–40% of the total electricity consumed in buildings [3,4]. Appropriate control strategies for lighting systems can achieve significant energy savings. Achieving energy savings and satisfying user lighting comfort are two major considerations for designing lighting systems [5–8]. Daylight is a lighting source that most closely matches the human visual response. The use of daylight can reduce lighting power consumption, increase users' lighting comfort and improve work productivity when it is used sufficiently and reasonably [9,10].

The rapid advancement in semiconductors has brought a new generation of light sources in form of LEDs [11]. LED luminaires have been widely used in commercial lighting systems because of their long lifetime, strong cost-competitiveness, high energy efficiency and greater design flexibility [12–14]. As the accurate and flexible control of LED luminaires, centralized dispatching and decentralized control to lighting loads become feasible [15]. A LED lighting system is incorporated more smart features and has a great potential for energy savings [16–18]. Reference [19] mainly described the technical conundrum in designing a smart lighting system, and various control methods have been summarized. It has become more feasible for LED lighting systems to participate in the operation and control of a weakly regulated power system [12]. Furthermore, LED lighting loads can serve as load reserves on load scheduling.

In this study, a smart LED lighting system was installed in a test office. The installed lighting system could achieve energy savings and satisfy users' lighting comfort by considering daylight contribution and the movements of users. It consisted of a DALI control module, multiple luminaires, distributed light and motion sensing modules and a micro-controller unit [20]. The light sensors could measure the total illumination levels arising from daylight and artificial lighting independently, whereas the motion sensors could monitor whether there was a user or not [21,22]. Intelligent devices with communication can provide an opportunity to control every LED luminaire [23].

Various studies about daylight contributions and smart lighting control systems have been performed [24]. In [2,25], researchers used a simple analysis method to evaluate the potential energy savings associated with electrical lighting when it is combined with daylight use. In [26,27], lighting power density requirements were proposed to estimate energy consumption. However, the movements of the user in the office were not considered in these studies. Motion sensors were installed to monitor users' locations for offering a comfortable illumination level in occupied regions [13]. In [28,29], a utility function was proposed to demonstrate user lighting preferences, which is based on Gaussian function. In this study,

* Corresponding author.
E-mail address: zhangwen@sdu.edu.cn (W. Zhang).

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the design focused on meeting user lighting preferences and saving lighting energy. More energy can be saved considering the daylight contributions and the real-time states in the office. A localized illumination rending strategy was presented that considered the user-occupied lighting comfort levels in [20], and two methods of lighting control were proposed to achieve energy savings and users' lighting comfort. This work would be more substantial if detailed experimental results were presented. In [30], a feed-forward neural network model was proposed to describe the relationship between the dimming levels of LED luminaires and the illumination level on a table without using simulation software. The actuation command to the luminaires was generated by a feedforward neural network control strategy. In [23], based on user preferences, a smart personal sensor network control in an LED lighting system was proposed. The system achieved significant energy savings. A fuzzy logic control system was established to control artificial lighting output by considering daylight contributions in [31]. The designed controller maintained the illumination level at a constant comfortable illumination level whereas the lighting comfort requirements had a wide range of specifications, according to users' lighting preferences. In [32], an intelligent algorithm RBFNN (radial bias function neural network) was proposed to obtain the illumination contribution from LED luminaires at any position inside the office. In order to acquire the optimal dimming levels of luminaires and design the target illumination levels, a PSO algorithm was used. Because LEDs are DC loads in nature, an LED smart lighting system played a critical role in the power management of buildings. Reference [34] provided a smart socket application for future smart buildings.

In this paper, the objective function was to minimize a weighted sum of lighting energy consumption in an office under the condition of lighting comfort. The relationship between the table illumination level and the LED luminaires was obtained by multiple measurements without daylight contributions. Light sensors and motion sensors were installed on tables to measure illumination and movement information. Based on the measured data, a fuzzy logic controller was designed to produce the required lighting output considering the lighting comfort requirements and user lighting preferences. A proportional-integral (PI) closed-loop control system was used to ensure that the actual output was in the range of the error requirement. The digital addressable lighting interface (DALI) protocol was utilized to establish a digital communication link between the controller and the LED luminaires.

The remainder of this paper is organized as follows. Section 2 describes the structure of a smart LED lighting system. In Section 3, the mathematical formulation of the LED lighting system is presented. Section 4 introduces the fuzzy logic controller considering daylight and lighting comfort. The simulation results and experiment verification are presented in Section 5 and Section 6, respectively. A final conclusions and an outlook for further work are given in Section 7.

2. Structure of a smart LED lighting system

The components of a smart LED lighting system are shown in Fig. 1. It consists of three parts: a measurement module, an information processing and decision-making module and an LED lighting system.

2.1. Measurement module

According to the design requirements, a smart lighting system requires monitoring of the real-time states in an office, including movement information and the illumination on the tables.

Light sensors were used to measure the worktable illumination from the daylight contributions and artificial lighting. Motion sensors were used to monitor whether the users are at the tables or not. Each light sensor generates a voltage signal that is related to the illumination level, and the installed motion sensor generates a low voltage level signal. The signals were sent to the controller once every second. When the motion sensors detected that all of the users have left the office, the lighting system was turned off after a delay.

The measured information was transferred to a data acquisition and processing module, which is an important element for decision-making strategies.

2.2. Information processing and decision-making

This section is the core of the design of a smart lighting system. It includes two main units: the information processing unit and the decision-making unit. Considering daylight performance and the movements of users in the office, the decision-making unit must process the information and provide dimming commands to the LED drivers to regulate the artificial lighting output. The main objective is to achieve energy savings under lighting comfort requirements. However, it is difficult to precisely define lighting comfort. A fuzzy logic controller was designed take these considerations into account. The output of the designed controller is a group of artificial lighting illumination requirements. With a PI closed-loop control system, the actual output of LED luminaires

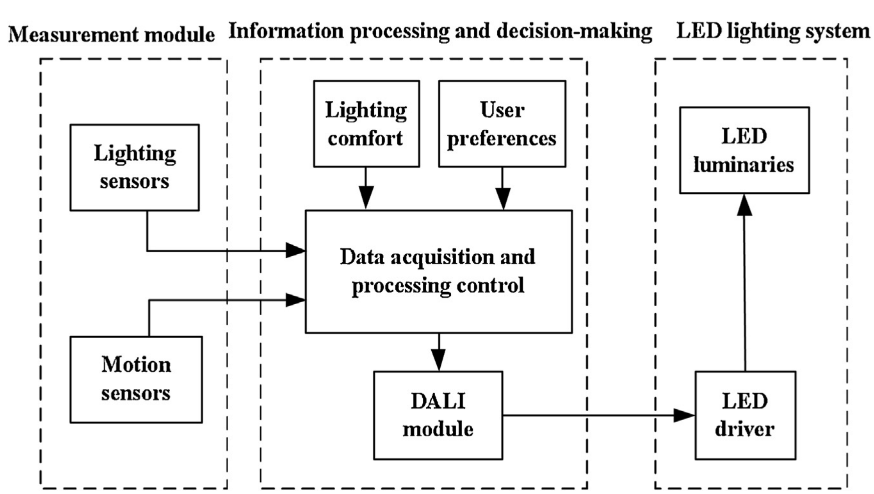

Fig. 1. Block diagram of a smart LED lighting system.