

Intelligent Lighting Control System for Energy Savings in Office Building

Khairul Rijal Wagiman¹, Mohd Noor Abdullah²

¹Institute of Industrial Training, Jalan Batang Melaka, 77500 Selandar, Melaka, Malaysia, +6065251224

^{1,2}Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia, +6074533017

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ABSTRACT

Lighting system is a crucial sub-system and consumes substantial electricity energy in the buildings. This paper proposes an intelligent lighting control system using artificial neural network (ANN). The minimization of dimming levels of luminaires has been considered as an objective function of the controller. Moreover, the light sensor field of view is also taken into consideration in objective function formulation. The proposed ANN controller has been tested on an actual office room of the Department of Mechanical Technology, Institute of Industrial Training, Selandar, Melaka, Malaysia. The simulation has been carried out using DIALux simulation lighting software. Based on the results, the proposed controller showed great performance in terms of adaptive less light sensor data and achieving dimming levels target that complies the European Standard EN12464-1. Furthermore, it can save energy up to 34%.

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Corresponding Author:

Mohd Noor Abdullah,

Faculty of Electrical and Electronic Engineering,

Universiti Tun Hussein Onn Malaysia, 86400,

Batu Pahat, Johor, Malaysia, +6074533017.

Email: mnoor@uthm.edu.my

1. INTRODUCTION

Lighting is one of the main sub-systems of building energy system and consumes large amounts of energy in the buildings after heating, ventilation and air conditioning (HVAC). The lighting system accounts 20 to 45% of the total energy is used in the buildings [1]. Several strategies have been proposed in order to minimize the electrical lighting energy consumption in the buildings namely, retrofits with energy efficient lamps such as T5 and light emitting diode (LED) lamps, reduce the maintained illuminance levels, occupancy control and daylight-linked control [2]. The LED lamps are well known as energy efficient and high performance lamps in terms of longer lifetime, high luminous efficacy and correlated colour temperature (CCT) and controllable. For retrofit with energy efficiency lamps [3–7], they analysed the economic evaluations including electricity cost and savings, payback period, life cycle cost and net present value.

In lighting system design and retrofit, the average maintained illuminance levels should be complied to the standard, for instance, European Standard EN12464-1 [8]. In practice, the average illuminance levels in the buildings will exceed the maintained illuminance levels due to the luminaires arrangement grids that are symmetry. For this reason, the dimming control is needed in order to reduce illuminance levels to comply the standard. The daylight-linked control is used the most due to its contribution to higher energy savings of lighting system in the buildings [9]. Mostly, previous works focused on the daylight-linked control to reduce energy consumption of lighting in buildings. The main objective of the lighting control is to minimize the dimming levels that will reduce the energy consumption of luminaires consequently. For LED luminaires under pulse width modulation (PWM), the dimming level is direct proportional to electricity energy that they

used [10]. Furthermore, LED lamp has special characteristics which are the light output that has linear relation to the consumed power and control signal [11]. The lighting system controllers can be divided into two types which are conventional and intelligent. Several works have developed the conventional controllers such as proportional integral (PI) [12,13] and proportional integral differential (PID) [14]. However, the conventional controllers have several drawbacks such as possessing constant parameters, large time delay when they are used alone and poor control performances [15]. For these reasons, several studies have developed hybrid methods which are hybrid conventional with intelligent controllers including fuzzy logic-PI [16] and fuzzy logic-PID [17]. Recently, there are various works that focus on the intelligent controllers due to their performance namely, self-adaptive algorithm [18], model based control (MBC) [19], multiple input multiple output (MIMO) [20] and illumination balancing algorithm (IBA) [21]. Artificial neural network (ANN) is widely used in the control system in multiple areas. For more specific example, the ANN has been utilized in the building energy systems such as in lighting [22] and HVAC [23]. In [22], the objective function is to minimize energy used from the lighting based on dimming levels of LED luminaires with satisfy table illuminance levels preference of occupants.

In this paper, the lighting system has been retrofitted with LED luminaires in order to propose intelligent lighting control system for energy savings in an office room. The lighting system design and measurements are referred to the European Standard EN12464-1. The objective function of the controller is to minimize dimming levels luminaires; due to the dimming level that has linear relation with the energy consumption of LED luminaires. Moreover, the sensor field of view has been considered in the objective function formulation. ANN has been used due to its most appropriate and well-performance method.

2. RESEARCH METHOD

This section discusses the research methods that are used in this study. The methods include daylight illuminance matrix model, lighting control objective and constraints and development of artificial neural network (ANN).

2.1. Daylight Illuminance Matrix

The model of daylight illuminance matrix is based on illuminance contribution from daylight on working plane. The illuminance measurement on working plane is referred to the European Standard EN12464-1 and its height is 0.75 meter (from the floor). According to the standard, the working plane is plotted with measurement points, where the maximum distance between points can be calculated based on equation stated in EN12464-1. The illuminance values on points will form the daylight illuminance matrix ($\mathbf{E}_{daylight}$) and can be expressed in equation (1) as follows:

$$\mathbf{E}_{daylight} = \begin{bmatrix} E_{1,1} & L & E_{1,N} \\ M & O & M \\ E_{M,1} & L & E_{M,N} \end{bmatrix} \quad (1)$$

where $E_{m,n}$ is illuminance level contributed from daylight for each measurement point.

2.2. Lighting Control Objective Function and Constraints

When the daylight illuminance matrix is obtained, the illuminance value at each point (E_j) on the working plane can be determined by multiplying the dimming levels of luminaires. The illuminance vector (\mathbf{E}) can be presented in equation (2) as follows:

$$\mathbf{E} = \mathbf{E}_{daylight} \times \mathbf{d} \quad (2)$$

where $\mathbf{E} = [E_1 \ L \ E_N]^T$ is vector of illuminance is measured on the working plane and $\mathbf{d} = [d_1 \ L \ d_K]^T$ is vector of the dimming levels of luminaires and K is number of K th luminaire.

The main objective of the study is to minimize the dimming levels of luminaires while maintaining the visual performance and comfort of occupants in the building. The visual performance refers to average illuminance levels (\bar{E}).

The objective function can be formulated based on equation (2). In this case, the lighting control system was divided into several controlling zones. The zones are determined by the number of light sensor installed in the room. It means, practically, a sensor will control several numbers of luminaires in the room. This concept is similar to lighting control by manual switches. The less number of light sensors installed will minimize the initial cost. The locations of the sensors were place based on the light sensor placement guide in [24].

The objective function which is the dimming levels of luminaires can be expressed in equation (3) as follows:

$$d_k = (E_{FB} - E_{FOV,k}) / E_{FB}, \quad k = 1, 2, 3 \dots K \tag{3}$$

where E_{FB} is maximum illuminance levels when a luminaire is ‘on’ under full brightness condition while the rest luminaires are in ‘off’ condition and $E_{FOV,k}$ is average illuminance value within field of view of K th sensor.

Based on result calculated in equation (2), the average illuminance levels (\bar{E}) can be determined using equations (4) as follows:

$$\bar{E} = \frac{1}{N} \sum_{j=1}^N E_j \tag{4}$$

The value of dimming levels is in the range of 0 to 1. 0 refers to ‘off’ condition while 1 refers to the highest brightness level of the lamp. The dimming level of luminaire capabilities relies on the type of luminaire and can be referred to the luminaire datasheet that is provided by luminaire manufacturers.

As mentioned in Section 1, the control signal has linear relation with energy consumed by LED luminaire. As a result, the total energy consumption (EC) of lighting with respect to the luminaires dimming levels can be defined as follows:

$$EC = \sum_{k=1}^K P_k d_k \tag{5}$$

where P_k is total rated power of luminaires in K th zone and d_k is dimming levels of luminaires in K th zone.

2.3. Artificial Neural Network (ANN)

In this study, the prior information of the daylight illuminance distribution has been obtained. For this reason, the artificial neural network (ANN) is the most appropriate method to be used. The ANN is one of the intelligent controllers that has capability to learn from experience (training process) and processes relationships between input and output simultaneously (recall process). In this paper, radial basis function network (RBFN) model was used as a controller in the lighting system. Basically, the RBFN consists of three layers that are input, hidden and output. The input and output layers are represented with vectors. Meanwhile, the hidden layer contains non-linear transformation and linear combiner functions. The objective function and its constraints of the proposed RBFN controller are presented in equation (6). The proposed RBFN model was developed using Matlab platform.

$$\begin{aligned} \text{Min } f(d) &= \sum_{k=1}^K d_k \\ \text{s.t.} \\ D_{min} &\leq d_i \leq D_{max} \\ \bar{E} &\geq \bar{E}_m \end{aligned} \tag{6}$$

where $f(d)$ is objective function which is the average dimming levels of all the luminaires, D_{min} , D_{max} are luminaire’s dimming capability lower and upper bounds, respectively, \bar{E} is average illuminance levels measured on working plane and \bar{E}_m is average maintained illuminance levels set point.

3. RESULTS AND DISCUSSION

The case study is an actual office room of the Department of Mechanical Technology, Institute of Industrial Training, Selandar, Melaka, Malaysia. The office dimensions are 20 m (length), 8 m (width) and 2.7 m (ceiling height). The room is illuminated by 24 T8 recessed luminaires that are arranged in the grid of 8 by 3. Each luminaire consists of 2x38W T8 lamps. The total lighting power density (LPD) and average illuminance levels (\bar{E}) are 11.4 W/m² and 514 lux, respectively.

The lighting system was retrofitted with the LED luminaires to benefit the advantages of LED lamp which are dimming control capabilities and energy efficient. The specifications of luminaire are as follow: total luminous flux of 3500 lm, total power of 34 W and recessed type. The retrofit lighting contributed 35 LED luminaires (5 by 7 grids). As results, the LPD and (\bar{E}) were 7.4 W/m² and 625 lux, respectively. It showed that the retrofit with LED luminaires had contributed to the reduction of the power of luminaires in room space and reduced the energy consumption from the lighting system. Moreover, it also increased the illuminance levels that would also the visual performance of occupants in the room. The layout of the luminaires in the office room is illustrated in Figure 1; the black squares represent the luminaires and the blue circles represent the light sensors. In this paper, 6 light sensors were placed on the ceiling of the room and the sensor field of view was considered half opening of 60°. The sensors arrangement and their indexing are showed in Figure 1.

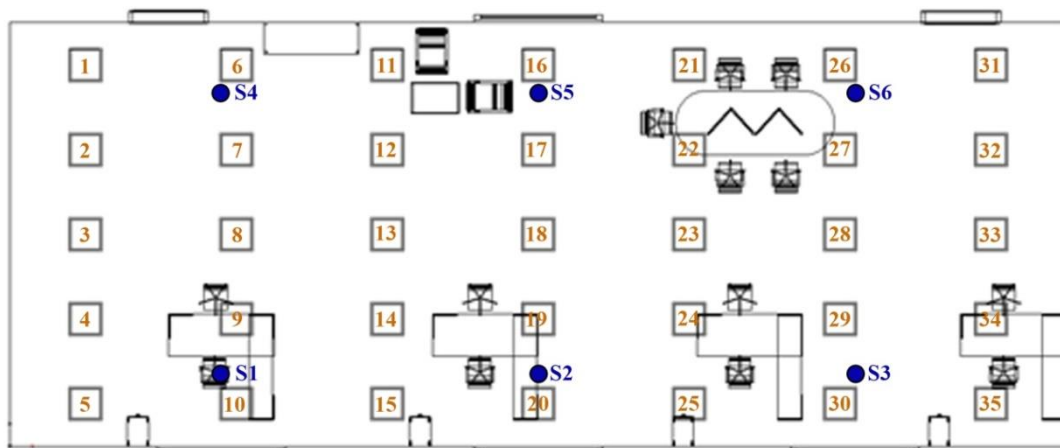


Figure 1. Top View of an Office Room

As mentioned in Section 2, the numbers of zones are determined by the numbers of sensors. As a result, the number of zones was 6. The details of luminaire indexing based on their zones are presented in Table 1.

Table 1. The Luminaire Numbers Based on Their Zone

Zone	Luminaire
1	3-5,8-10
2	13-15,18-20,23-25
3	28-30,33-35
4	1,2,6,7
5	11,12,16,17,21,22
6	26,27,31,32

In this study, the simulation of daylight was carried out using DIALux under the clear sky condition, during office hours from 08:00 to 17:00 with 1 hour of interval time on the first day of the months of September, October and November in 2017. Figure 2 shows the simulation results of the average illuminance from daylight in the office room. The simulated data was recorded for training process purpose. The data was divided into two parts which were input data and target data. The inputs represent the average illuminance

values within sensor field of view (E_{FOV}) vector, while the outputs represent the dimming levels of luminaires (d) vector.

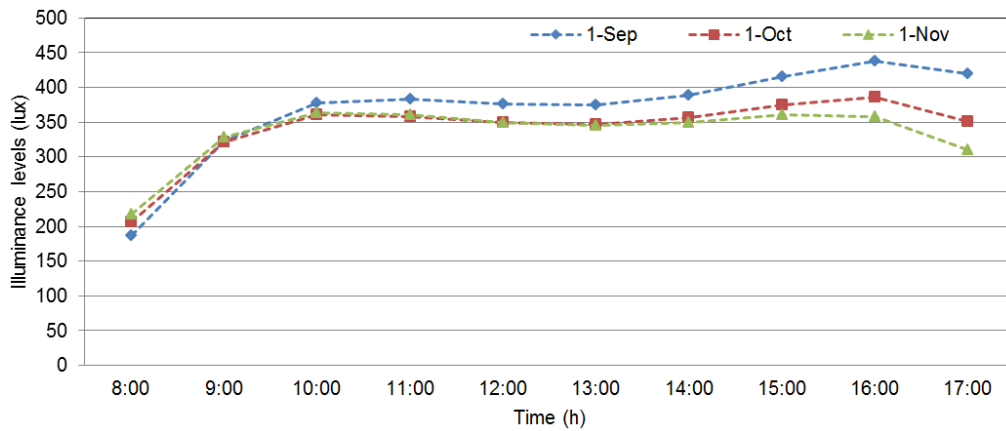


Figure 2. Average Daylight Illuminance in the Office Room

Figure 3 shows the architecture of the proposed RBFN as a controller in lighting system. It can be seen the number of neurons for input and output layers is 6. Meanwhile, the hidden layer consists of radial basis and linear layers contain 30 and 6 neurons, respectively.

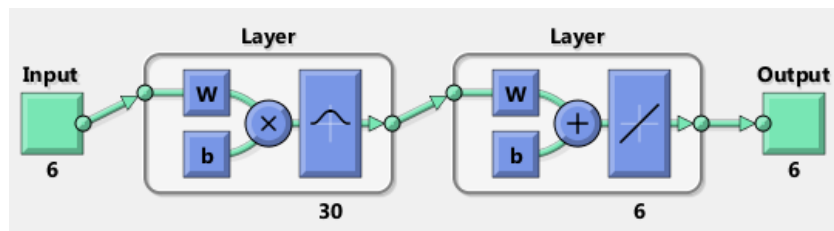


Figure 3. Architecture of Proposed RBFN

In order to test and validate the proposed RBFN model, the light sensor output data were obtained from DIALux simulation on 5th October 2017 during the office hours under clear sky condition. The light sensor output data are the input vector of the controller (RBFN model). The controller processes the sensor data and generates the dimming levels for luminaires. The dimming levels of luminaires results under the proposed RBFN controller for selected zones and their mean are presented in Figure 4. Based on Figure 4, the highest dimming levels of luminaires for the whole zones at time 8:00 due to at that time, the illuminance distribution from daylight across the room was the lowest compared to other times. The mean dimming levels of luminaires for the whole working hours was 0.35. The dimming levels of luminaires at Zone 4 showed the highest dimming value due to the zone was the lowest illuminance distribution contribution from daylight.

The DIALux software simulation was carried out in order to validate the illuminance levels that were fully satisfied to the EN12464-1 based on the dimming levels generated from the proposed controller. Figure 5 shows the average illuminance levels under the proposed RBFN controller. As can be observed from Figure 5, the average illuminance levels under the proposed RBFN controller was archived above the threshold of \bar{E} that was specified in the EN12464-1 which is 500 lux. From the simulation results, the isoline from both daylight and artificial light at time 13:00 is depicted in Figure 6.

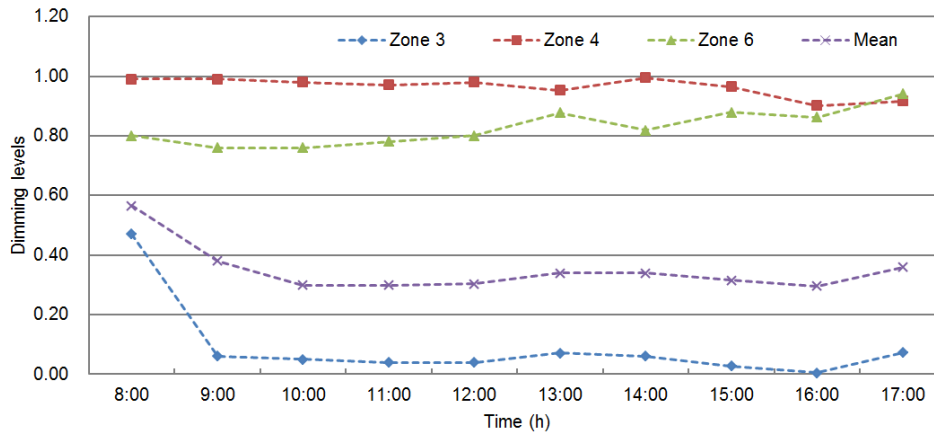


Figure 4. Dimming Levels of Luminaires Results for Selected Zones and Their Mean

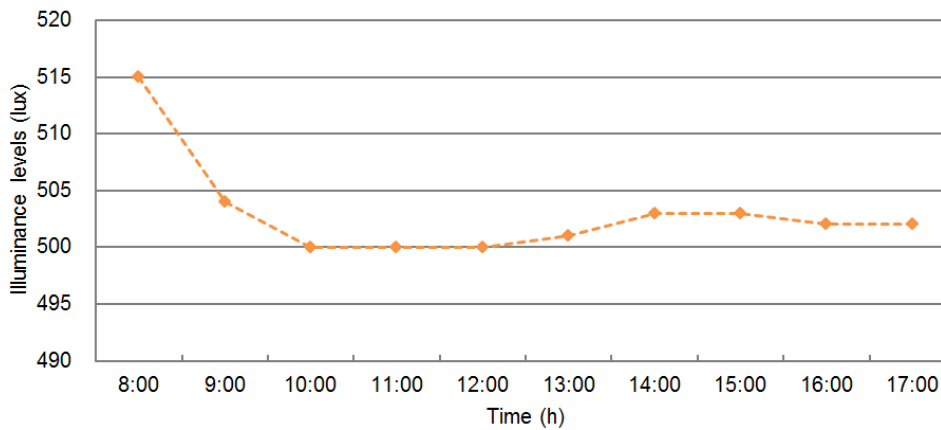


Figure 5. Average Illuminance Levels Under the Proposed RBFN Controller

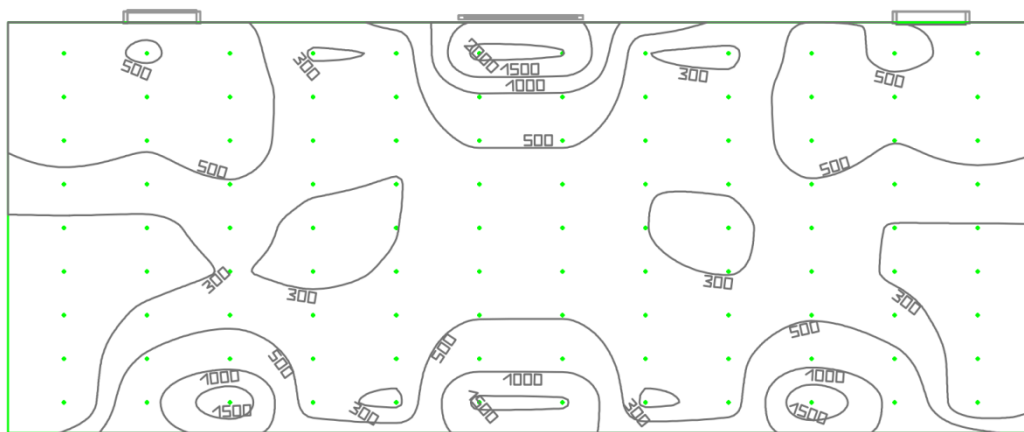


Figure 6. Isoline from Both Daylight and Artificial Light at Time 13:00

The total energy consumption (*EC*) of all luminaires under the proposed RBFN controller was calculated according to the equation (5). Figure 7 presents the energy used under the proposed RBFN controller during office hours. By considering the electricity tariff for the low voltage commercial buildings (tariff B) from electricity utility of Malaysia which is Tenaga Nasional Berhad (TNB) of RM0.435/kWh [25],

the total electricity cost was RM1.14/day. Energy saving (ES) can be described as the difference between the energy consumption of existing and proposed systems, and is divided by the energy consumption of existing system. ES is the most widely used to evaluate energy performance and most studies have expressed in percentage (%). As a result, the ES of the proposed RBFN controller was 34%.

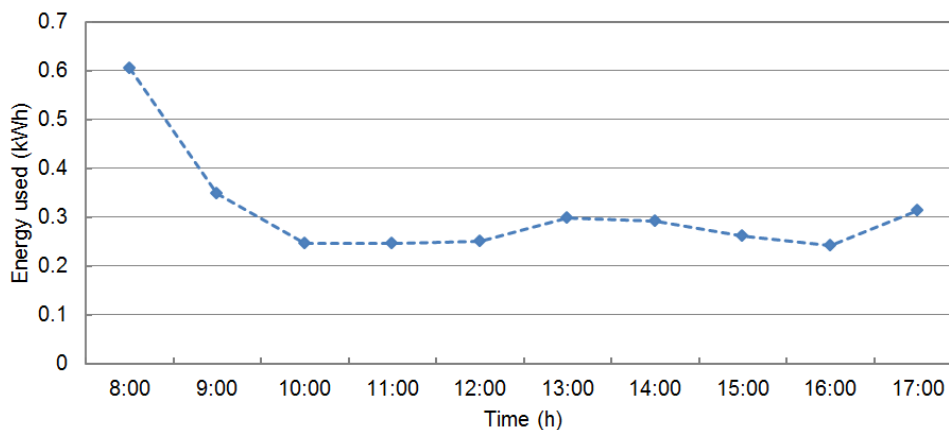


Figure 7. Energy Used under the Proposed RBFN Controller

4. CONCLUSION

This paper presents an intelligent lighting control system using RBFN model in an office building. The objective function of the controller is to minimize the dimming levels of luminaires that satisfy the minimum of \bar{E} that is stated in the EN12464-1. The light sensor field of view was considered in order to calculate the dimming levels of luminaires for the proposed RBFN controller. The proposed controller was tested and validated at an actual office room and was simulated using DIALux software. The results showed that the proposed RBFN controller was showed great performance in terms of achieving dimming level targets and satisfied the EN12464-1. Furthermore, the energy savings recorded from the proposed RBFN controller was 34%.

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