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Indoor-Lighting System Design Using Simultaneous Control of LEDs Lighting Intensity and Roller Blinds' Opening for Economic Energy Consumption

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***Abstract*—**In this paper, daylight harvesting is used to minimize the power consumption - required for indoor lighting - using electric roller blind. Smart controller is designed to adjust - based on the preset light intensity - the position of the roller blind's stepper motor, and consequently the roller blind opening for better utilization of the daylight entering the room. If the desired illuminance level (IL) is not achieved for any reason, the smart controller adjusts the LED circuit current to boost the light intensity to achieve precisely the desired IL. Comprehensive tests - carried out using MATLAB-Simulink to verify the performance of the proposed smart controller – reveal that the proposed controller successfully maintains the indoor lighting intensity at the desired IL. Results of the techno-economic analysis - performed to evaluate the benefits of employing the proposed controller – show that an energy saving of about 62% is achieved, and that the lifetime of the LED circuits can extend to more than 20 years.

***Keywords*—** Energy saving; Light control; Smart lighting; Illuminance level; Daylight harvesting; Smart controller.

1. INTRODUCTION

According to the UN's Brundtland Commission popularized in 1987, sustainability is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable energy is energy that is continually available and does not harm the environment and can help improve public health. Daylight is a free of charge sustainable clean energy source, and it is available for almost 12 hours daily. Efficient utilization of the daylight harvesting techniques can reduce drastically the carbon dioxide emission and hence reduce the pollution and assist in controlling the rise in global temperature. Additionally, daylight harvesting creates a visually pleasing, healthier and more productive environment for building occupants. In industrial and residential applications, different technologies are being developed nowadays to utilize the daylight in electrical generation, heating process and natural indoor lighting.

A comprehensive review of daylight harvesting and methods of its control in offices and buildings is introduced in [1-3]. In these papers, advanced daylight harvesting systems (DHS) that are designed to maximize the energy-saving potential of day lighting, while improving comfort and visual performance at an "affordable" cost, are discussed. Different study cases in these review papers show that energy saving potential is 20-60% compared to non-dimmed installations; however, technical robustness, architectural integration and human acceptance deserve more attention during the design and commissioning of the DHS.

The designers consider different techniques, depending on the applications, to control the DHS. Dynamic and static shading devices are used in to optimize the power consumption

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of lighting and heating, ventilation, and air conditioning (HVAC). In [4, 5], the use of blinds and electrochromic windows and an economic analysis for shading the indoor spaces and hence control the heat transfer to outside for better HVAC design are discussed. In [6], the shading is evaluated using different glassing systems such as standard double-glazing system, systems with granular silica aerogel in interspace and double lazing with sunlight control films. Two remodeling methods using polymer dispersed liquid crystal (PDLC) films, which can adjust solar radiation for old office buildings are proposed and analyzed. In [7], the shading is evaluated using different glassing systems such as standard double-glazing system, systems with granular silica aerogel in interspace and double-glazing with sunlight control films. The paper showed that the indoor daylight harvesting achieved by standard glazing is 500 Lux approximately.

Smart curtains are also used widely in DHS applications. The performance of curtain wall-facades of varying designs incorporating photovoltaics opaque and semitransparent on energy performance, daylight harvesting level for an apartment within amid-rise apartment building is discussed in [8]. Arduino is used with different sensors in [9-11] to integrate either closing or opening operation of the curtains in the control system of smart home to optimize the utilization of the daylight and to reduce the power consumption. Smart wireless control of the curtain is provided in [12] to either open or close the curtain using a mobile phone. This intelligent curtain can work in the manual mode, automatic mode and sleep mode, and can be carried out by the button and mobile phone app mode loop switch.

Beside the scientific efforts to control the daylight harvesting for indoor economic illumination, other efforts are being spent to use and to control less cost lighting devices such as LED's in the indoor lighting for better users' satisfaction. Remotely controlled LED lighting system uses Android apps for handheld devices is discussed in [13]. In this paper, the ZigBee standard is followed to design a wireless data communication. Smart LED control systems equipped with movement sensors, brightness control and /or color temperature adjustment using different technology approaches is discussed in [14-16].

Several scientific work incorporates the utilization of the daylight in the design of the indoor lighting control. In [17], Mahmoud utilized the background daylight as base source of the light, and then control the LED lighting system to achieve the desired value of the Illuminance level (IL). Arduino is used as a controller unit to receive the background light intensity signal from the light sensor and to adjust gradually the lighting intensity in the room to meet the desired IL value or higher. Movement sensor is used to switch off the light in case there is nobody in the room. The proposed methodology in [17] is not precise as it does not consider the over-IL cases, and it accepts that the light intensity in the office to be higher than the desired value if the daylight inside the room is greater than the desired IL value. Also, the glare problem is not solved in his article. In [18], the authors use set of switches that control lighting circuits (a switch per circuit) and another set of light sensors. All these devices are integrated in one logic algorithm to utilize the daylight with the lighting circuits to adjust the light intensity in the room. The proposed algorithm, first turns off all lights, then turns on one light circuit at a time and records the light's impact, and repeats this process till the desired light intensity is achieved. This suggested method is not accurate because although it considers the daylight level in the initial calculation of the room light intensity, it does not control the amount of daylight entering the room. It also does not integrate occupancy detectors in the algorithm. Also, as the method uses many switching and sensor devices, this make the method expensive and not reliable. In [19], Suradi et al. proposed a system that utilizes the daylight by opening automatically the windows if the IL setting in Arduino is between 110 and 210 Lux. Arduino stops window opening process if the measured IL is greater than 210 Lux. The window receives closing signal in case there is no daylight available. This system is not accurate in controlling the daylight intensity entering the room, and the controller has narrow range of the lighting intensity adjustment inside the room. In [20], Cruz et al. proposed a solution for smart rooms to conserve energy in the buildings by integrating the daylight harvesting with a curtain and light appliances in one memory protection unit (MPU) controller. In this method, a light dependent resistor (LDR) is used to control servo motor that control the window curtain to maximize the use of daylight. However, the project failed to implement an efficient use of the daylight to maintain the light intensity level.

Techno-economic analyses are performed in several articles that include direct and indirect benefits obtained from using different intelligent lighting and heating systems. In these analyses, "direct benefits" are categorized in two parts; operational and maintenance cost. For "indirect benefits", are also categorized in two parts, more oil/gas sale opportunity and reduction of pollution [21-26].

From literature review, we realize that many research works were done in the daylight harvesting subject; however, none of these works introduced an integrated design that include: i) LED control, ii) daylight diffuser window and iii) motorized roller blinds to precisely and economically control the indoor IL requirement.

In this article, accurate approach for an integrated design of indoor lighting system - utilizing the daylight harvesting, LED lighting system and daylight diffuser window - is introduced. In this approach, adaptive dual control is used for roller blinds and LEDs simultaneously in order to minimize the power consumption of the indoor illumination system and achieve, precisely, the desired light intensity level. In addition, this paper introduces a techno-economic analysis that support the design benefits.

The rest of this paper is organized as following: section 2 presents the design of the proposed smart lighting system. The proposed lighting system response and results are introduced in section 3. Techno-economic analysis is provided in section 4. Finally, section 5 summarizes the entire work and gives the conclusions and recommendations.

2. DESIGN OF THE PROPOSED INDOOR SMART LIGHTING SYSTEM CONTROLLER (ISLSC)

2.1. Design Criteria

As the sun is considered at infinity distance from the window, the lighting intensity projection on the window is assumed to be uniform. 500 Lux is considered as the average daylight intensity passing through the window when it is fully open [7]. When the blind fully close, no daylight is penetrating the room. The daylight passing the window is linearly proportional to the roller blind opening percentage. In most indoor applications, the desired IL level does not exceed 500 Lux. Table 1 illustrates the minimum illuminance level (E_{min}) in Lux requirement for different indoor application [27].

Table 1. E_{min} requirement for different indoor applications.

Facility type	Area or task type	E_{min} [Lux]
General	Entrance halls or corridors	100
Offices	Typing ,writing, reading	500
Offices	Technical drawing/working on computer	500-750
Offices	Conference rooms/archives	200-500
Restaurant	Kitchen/dining room	300-500
Schools	Classrooms/library and laboratories	300-500
Hospital	Waiting rooms/operating theater	200-1000
Residential	Kitchen	300
Residential	Dining room	100–250
Residential	Living room	200
Residential	Bedroom	150
Residential	Bathroom	200
Residential	Hallway	100–200

As this ISLSC will be installed in controlled temperature area, the impact of temperature variation on the IL sensor accuracy is not considered.

For the base case, the design considers rooms and offices that have one window, as this is the most common rooms’ design. However, the special cases of rooms with more than one window is also discussed in a separate paragraph hereinafter.

2.2. Components

The proposed system is composed of the following components:

2.2.1. Daylight Diffuser Window

In general, the greatest benefits of daylight harvesting result from maximizing a building’s northern and southern windows while minimizing its eastern and western windows. Northern and southern lighting is easily to be controlled. Northern light is relatively diffuse, with little glare, and often does not require the use of external shading. Southern daylight is abundant, with more opportunity to direct lighting deeper into the room, but glare must be controlled to manage this opportunity. Windows to the east and west, as well as unshaded southern windows, can cause excessive glare due to low sun angles and excessive cooling loads due to difficulty in shading. However, using ISLSC with properly selected roller blinds - that can reflect-back some solar energy to outside - and daylight diffuser window - that distribute the day light inside the room- help in reducing both glare and cooling load because only the required daylight is allowed to penetrate into the room without glare effect.

The degree of daylight diffusion and the maximum IL entering the room is not only very important for the visual perception but also to, efficiently, control the indoor light. Therefore, quality diffuser window is required as essential component in the proposed design. Regardless of the sun angle, wide-angle daylight diffuser window provides equally bright [28].

Fig. 1 illustrates the measured distribution of what comes out of the daylight diffuser window when light shines 45°. A light measurement for the daylight radiant intensity leaving the wide angle daylight diffuser window is shown in Fig. 2 [29].

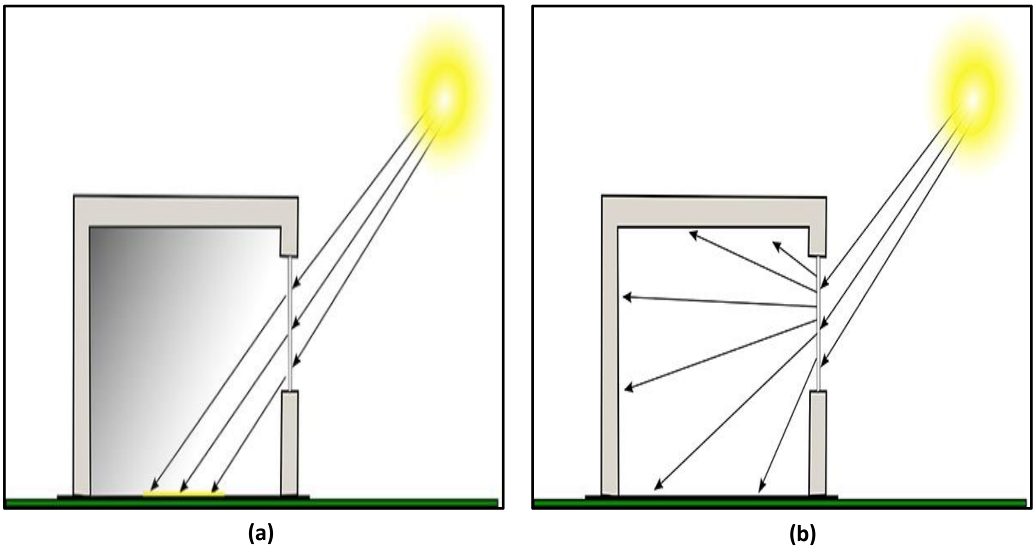

Fig. 1. Effect of the daylight diffuser window: a) without the diffuser; b) with the diffuser.

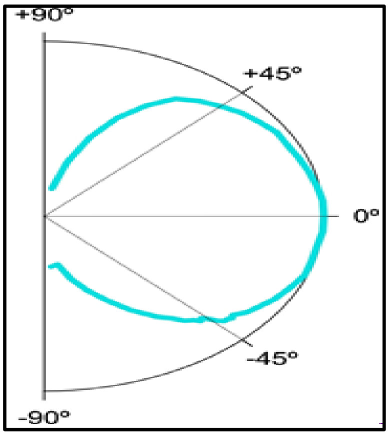

Fig. 2. Measurement of daylight radiant intensity.

2.2.2. *LDR Transducer*

Two IL sensors based on dependent resistor technology are used. LDRs are very useful especially in light/dark sensor circuits. Normally, the resistance of an LDR is very high; typically, around 1 MΩ at 10 Lux or less. But when illuminated with light, the resistance drops dramatically. The LDR IL transducer is chosen to be used in this proposed smart lighting system controller because of its high sensitivity, ease of employment in the control circuit, low cost (of approximately 20 $/piece) and its high light-to-dark resistance ratio. The main disadvantages are its slow response and low temperature stability. However, these disadvantages do not affect the performance of the indoor lighting control as fast response is not a concern and the indoor temperature does not go too low.

First IL transducer (DT) must be installed near the window that will receive the daylight intensity. The function of the second IL transducer is to measure the average IL inside the room (RT). This can be done using group of the transducers if required, in case the room area is large and have more than one window .

2.2.3. Stepper Motor System

The proposed method uses stepper motor drive together with stepper motor to provides linear control position for the roller blind. The step size of the stepper-motor is 1^{o} for each unit input. This is to achieve precise control for the operation of roller blind. In this position control model, the input reference to the stepper motor drive is the desired number of steps. So, if the light intensity is taken as input to the stepper motor drive, 500 Lux is equal to 500 steps. Typical price for such fractional horsepower stepper motor including the drive and the gearbox is approximately 50 $.

The differential equations for the stepper motor are given as:

$$e_A = -K_m.\omega.sin(N_r.\theta) \tag{1}$$

$$e_B = K_m\omega.cos(Nr_r.\theta) \tag{2}$$

$$\frac{di_A}{dt} = \frac{v_A - Ri_A - e_A}{L} \tag{3}$$

$$\frac{di_B}{dt} = \frac{v_B - Ri_B - e_B}{L} \tag{4}$$

$$\frac{Jd\omega}{dt} + D\omega = T_e \tag{5}$$

$$T_e = -K_m\left(i_A - \frac{e_A}{R_m}\right)sin(N_r.\theta) + K_m\left(i_B - \frac{e_B}{R_m}\right)cos(N_r.\theta) - T_d sin(4N_r.\theta) \tag{6}$$

$$\omega = \frac{d\theta}{dt} \tag{7}$$

For constant angular speed

$$\theta = \omega.t + \theta_0 \tag{8}$$

where: e_A and e_B are the back electromotive forces induced in the two phase windings *A* and *B* of the motor, respectively, i_A and i_B are the *A* and *B* phase winding currents, v_A and v_B are the A and B phase winding voltages, K_m is the motor torque constant, N_r is the number of teeth on each of the two rotor poles where the full step size parameter is $(\pi/2)/N_r$, *R* is the winding resistance, *L* is the winding inductance, R_m is the magnetizing resistance, *D* is the rotational damping, *J* is the inertia, ω is the rotor speed, θ is the rotor angle and θ_0 is the initial rotor angle, T_d is the detent torque amplitude.

MATLAB – Simulink stepper motor driver block is used to create the required pulse trains for the stepper motor presented in the above mentioned Eqs. (1) to (7) [30].

2.2.4. Roller Blind

Motorized roller blinder for standard-size window is used to control the daylight access to the room. The cost of a blind designed for ZigBee smart home automation system is approximately 15 $.

2.2.5. LED Light System

As the objective of this article is to minimize the power consumption of the indoor lighting, LED lighting system has been chosen because of its reliability, low running cost and its linear characteristic for light intensity with the current. Most common LED's require a forward operating voltage between 1.2 to 3.6 V with a forward current rating of about 10 to 30 mA [31]. Occupancy sensor is used to switch on/off the light circuit based on the movement in the room.

2.3. Control Circuit Description

In the proposed control circuit, first IL transducer, DT, receives the daylight intensity continuously. The transducer's output electrical full scale signal is 10 mA, which represents 500Lux. This electrical signal is - continuously - transferred back to its corresponding daylight IL value using a gain factor of 50000. The actual daylight harvesting value is compared with the desired IL value for the room, and the error is used as reference input to the stepper motor drive to control the closing of the roller blind to allow only the desired IL to be achieved. The second IL transducer, RT, simultaneously and continuously measures the light intensity inside the room, and the controller compares it with the desired IL value. If the desired IL is achieved, no further lighting will be required from the LED circuit. If the required IL is still higher than the room IL, then the controller will send a signal to the LED circuit to increase the current, and hence adapt the light intensity till the desired IL is achieved. Fig. 3 illustrates the Simulink circuit that is used to implement this control scheme. Arduino or any simple PLC with a cost of 50 $ can be used easily to build such smart controller.

It is worth to mention that based on the aforesaid control logic, this ISLSC is a general unit. Even if the daylight harvesting exceeds 500 Lux due to the orientation of the window, minor calibration for the stepper motor drive will be required to maintain same efficient operation of the ISLSC.

3. RESULTS AND DISCUSSION

3.1. ISLSC Response

Using the circuit illustrated in Fig. 3, five study cases are carried out to verify the performance of the proposed ISLSC. These cases are selected to cover the main IL values listed in Table 1. The values of the desired illuminance level, selected for the studied cases are 100, 200, 300, 400 and 500 Lux. Figs. 4 to 8 illustrate the results of these five test cases.

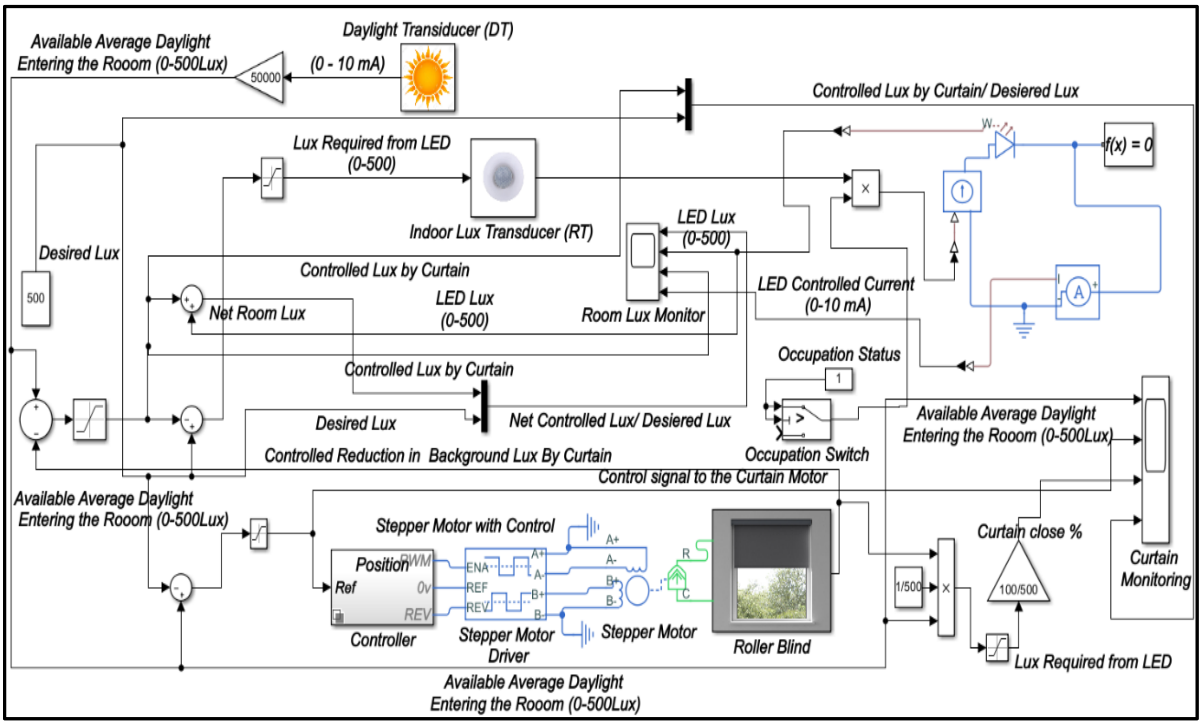

Fig. 3. ISLSC Simulink circuit.

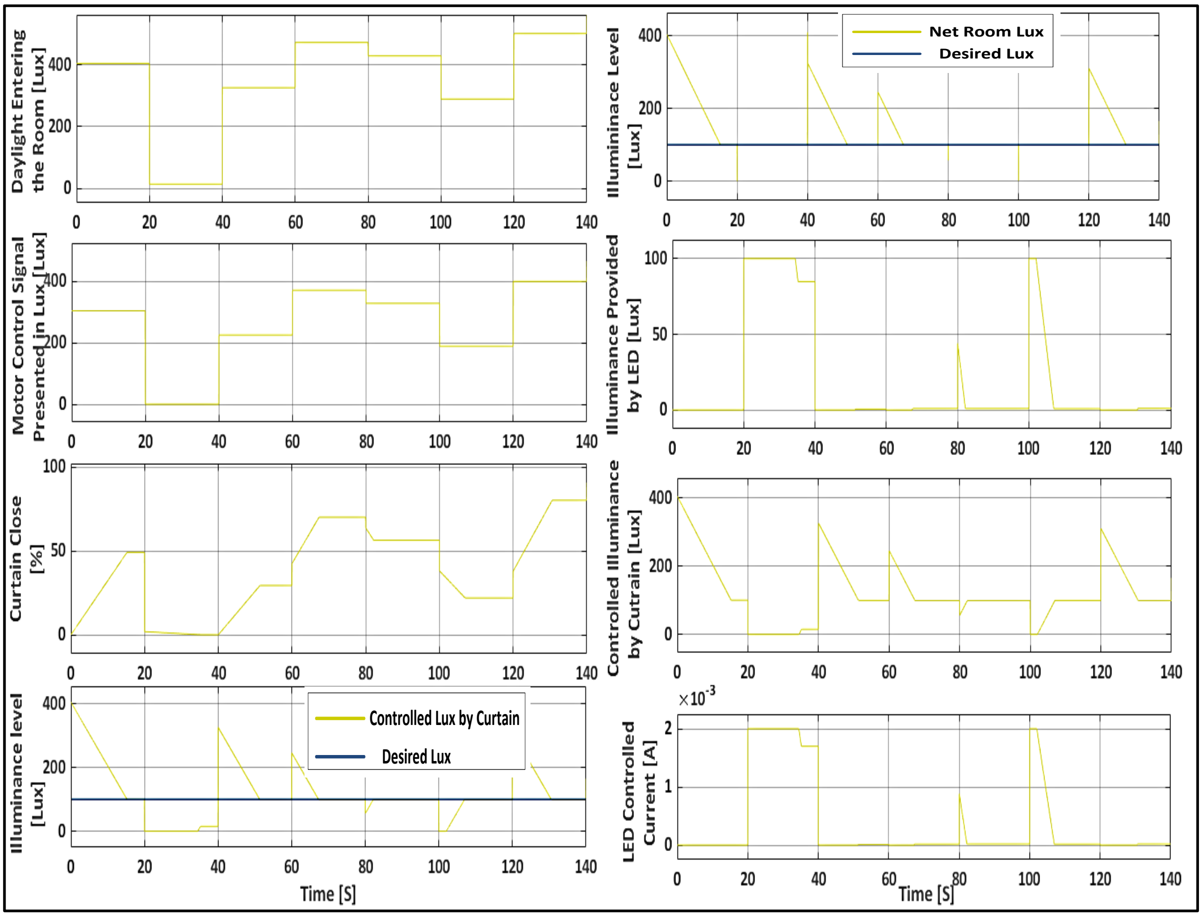

Fig. 4. Results for the desired illuminance level of 100 Lux.

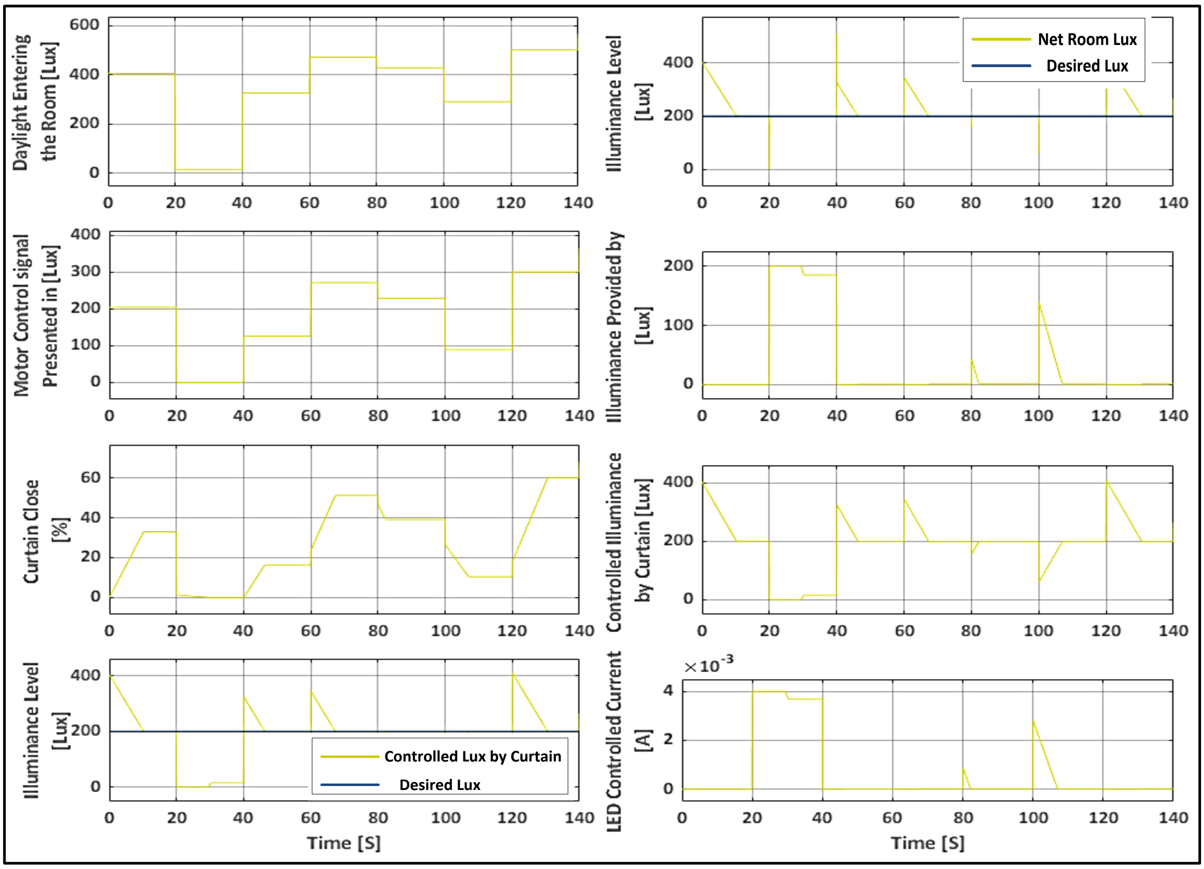

Fig. 5. Results for the desired illuminance level of 200 Lux.

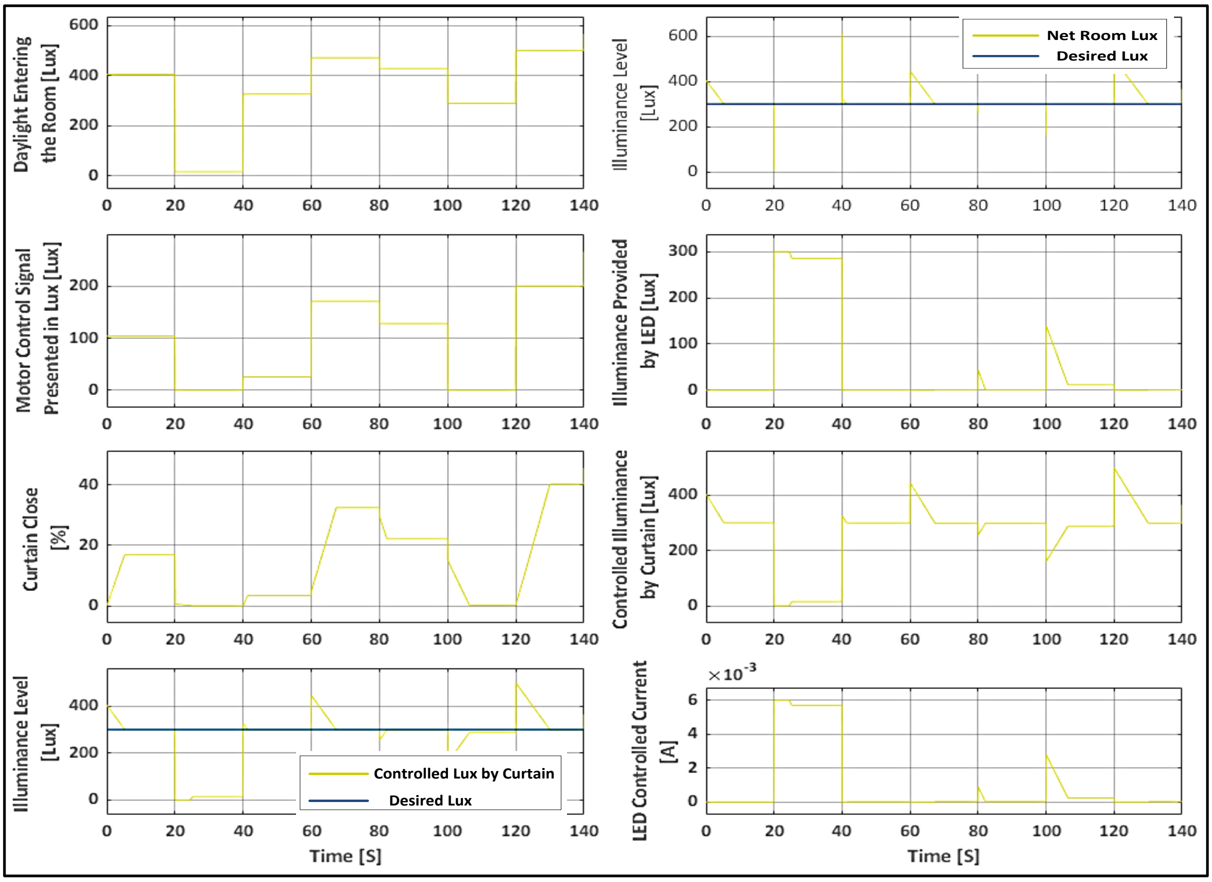

Fig. 6. Results for the desired illuminance level of 300 Lux.

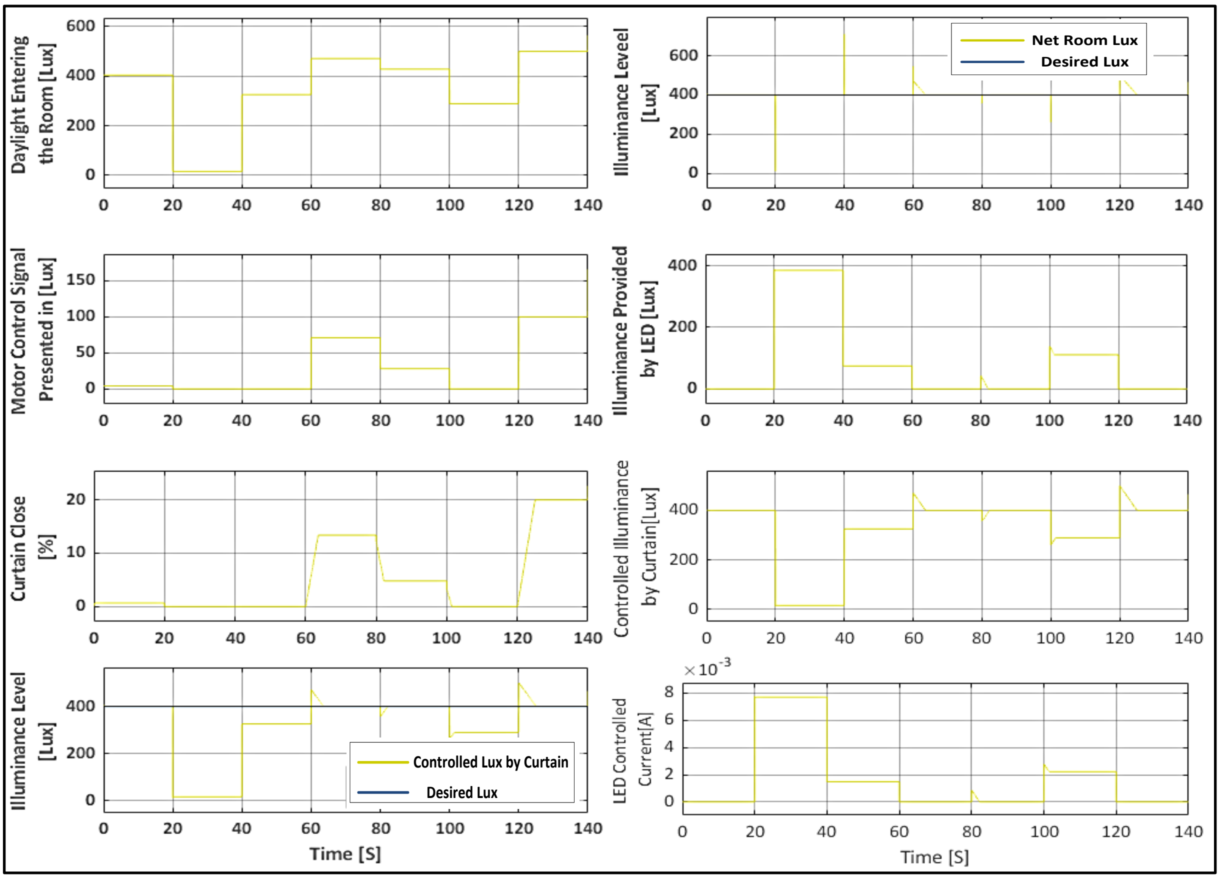

Fig. 7. Results for the desired illuminance level of 400 Lux.

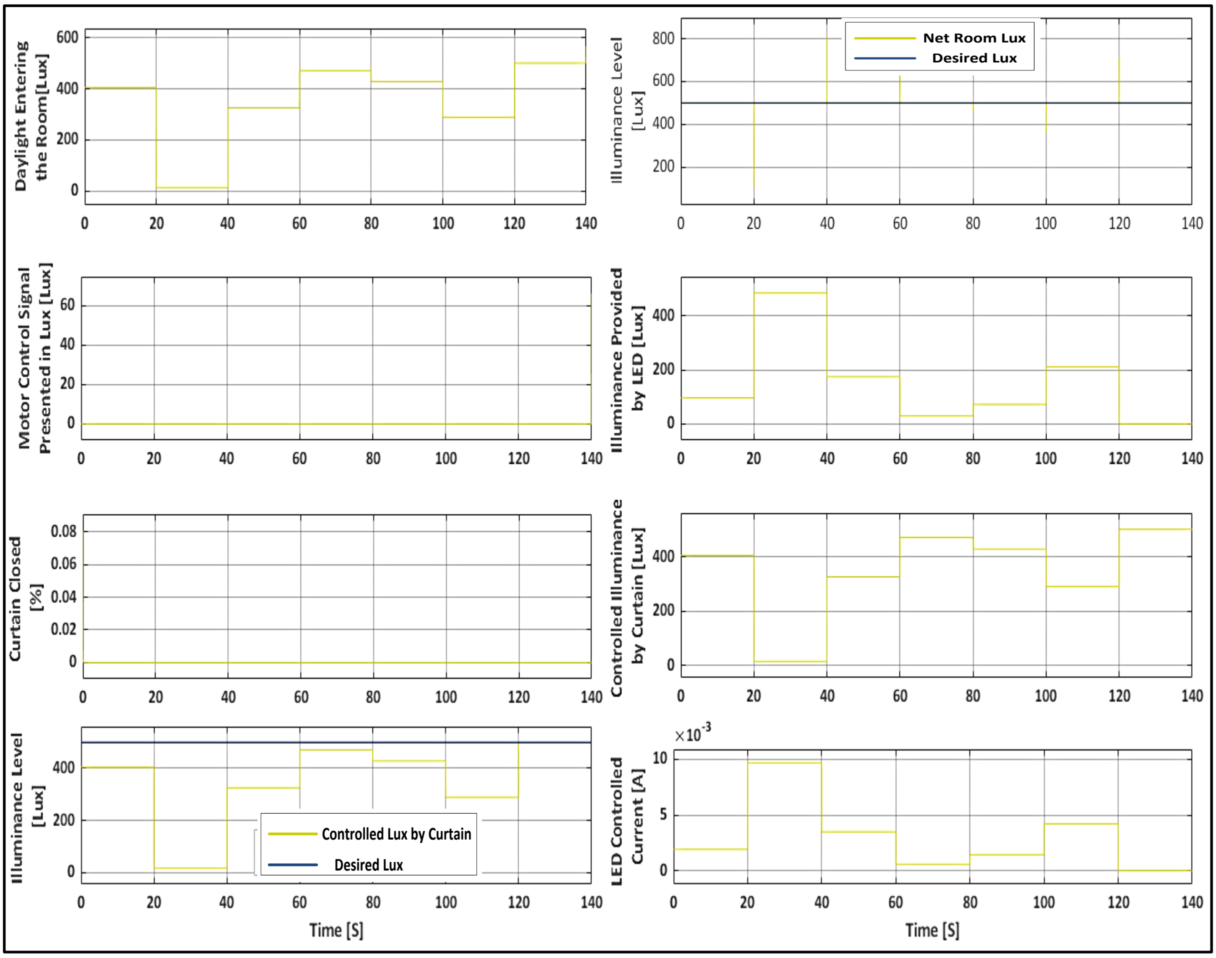

Fig. 8. Results for the desired illuminance level of 500 Lux.

The obtained results that in few seconds (maximum 10 s), the proposed ISLSC succeeded in controlling the light intensity inside the room to achieve, precisely, the desired IL value for all the five test cases by properly controlling the daylight harvesting passing through the window and simultaneously control light that can be obtained from the LED circuit. Here, the priority is given to the daylight harvesting - to be used to achieve the desired IL - and if required, the LED circuit operates to compensate any further need of light to achieve the desired IL value. Therefore, by this methodology, ISLSC minimizes the power consumption of the indoor lighting.

3.2. Base Case for Rooms with One Window

From the design criteria, 500 Lux is considered as the average daylight harvesting intensity passing through the window when it is fully opened. Also, from Table 1 and in most indoor applications, the desired IL level does not exceed 500 Lux. Considering the fact that sun is at infinity distance from the window, and the lighting intensity projection on the window can be assumed uniform, the maximum closing of the window blind to meet the minimum light intensity of 200 Lux that is desired to be achieved in offices is 60%.

Also, it worth to highlight that any uncertainty in the DT readings or stepper motor position, either by plus or minus, the exact desired lighting intensity will still be achieved by the LED circuit drive control, which is responsible to correct any error at the end.

For any possibility of overshoot or oscillation in either LED control loop or stepper motor control loop, standard PID controller may be designed and added in the implementation phase based on actual response of the system.

3.3. Special Case for Rooms with More than One Window

These are rare cases compared with the rooms that have only one window. However, in such cases, additional IL transducer needs to be fixed at each window that has uncontrolled blind, in order to measure the uncontrolled daylight entering the room. The total contribution from all these windows needs to be calculated and deducted from the desired IL instantaneously. By this way, the same ISLSC can work efficiently.

4. TECHNO-ECONOMIC ANALYSIS

As mentioned earlier, in the techno-economic analysis, "direct benefit" is categorized into two parts; operational and maintenance costs, and the "indirect benefit" is categorized also into two parts, introducing more oil/gas sale opportunity and reduction of pollution. The cost of this intelligent lighting system is negligible compared with other lighting systems such as cables, light fixtures, switches, conduits and installation work.

In this section, techno-economic evaluation is carried out to calculate the direct and indirect benefits obtained from using the proposed ISLSC in a typical indoor lighting for an office. In this case study, 14 hours starting from 7:00 am to 9:00 pm are considered as working hours for the office. Occupancy sensor is assumed to switch on the light at 7:00 am and switch off the light at 9:00 pm. The daylight data is taken from [32]. The required indoor lighting intensity of 400 Lux is selected from Table 1 for the "conference rooms/archives."

In this case, the maximum available daylight that penetrates from the window is 900 Lux. Therefore, minor calibration is required to adjust the roller blind to set 100%-closing position to zero Lux, and to set 0%-closing position to 900 Lux. This can be done either from the stepper motor drive or by changing the gearbox connecting the motor to the roller blind.

This case study is modeled in Simulink using the same ISLSC discussed in sections 2 and 3 after adapting the "curtain percentage close" gain to match 900 Lux instead of 500 Lux. The purpose of performing this this simulation is to insure that ISLSC is still working efficiently after the minor calibration, and also to calculate the energy saving and hence, evaluate the "direct" and "indirect" benefits that can be obtained using the proposed ISLSC.

In Fig. 9, the results of 14 hours operation of the office - from 7:00 am to 19:00 pm - is illustrated. It is clear that the roller blind tries always to pass only the desired IL from the daylight to the room. If the available daylight harvesting is less than the desired IL value, ISLSC resources the difference in the IL from the LED circuit to maintain the lighting intensity of 400 Lux all the time. The results show efficient and fast performance of the ISLSC. The spicks in the graph are due to the sudden change of the daylight harvesting level, which is not there in the real situation. Therefore, more smooth lighting control is expected in real application.

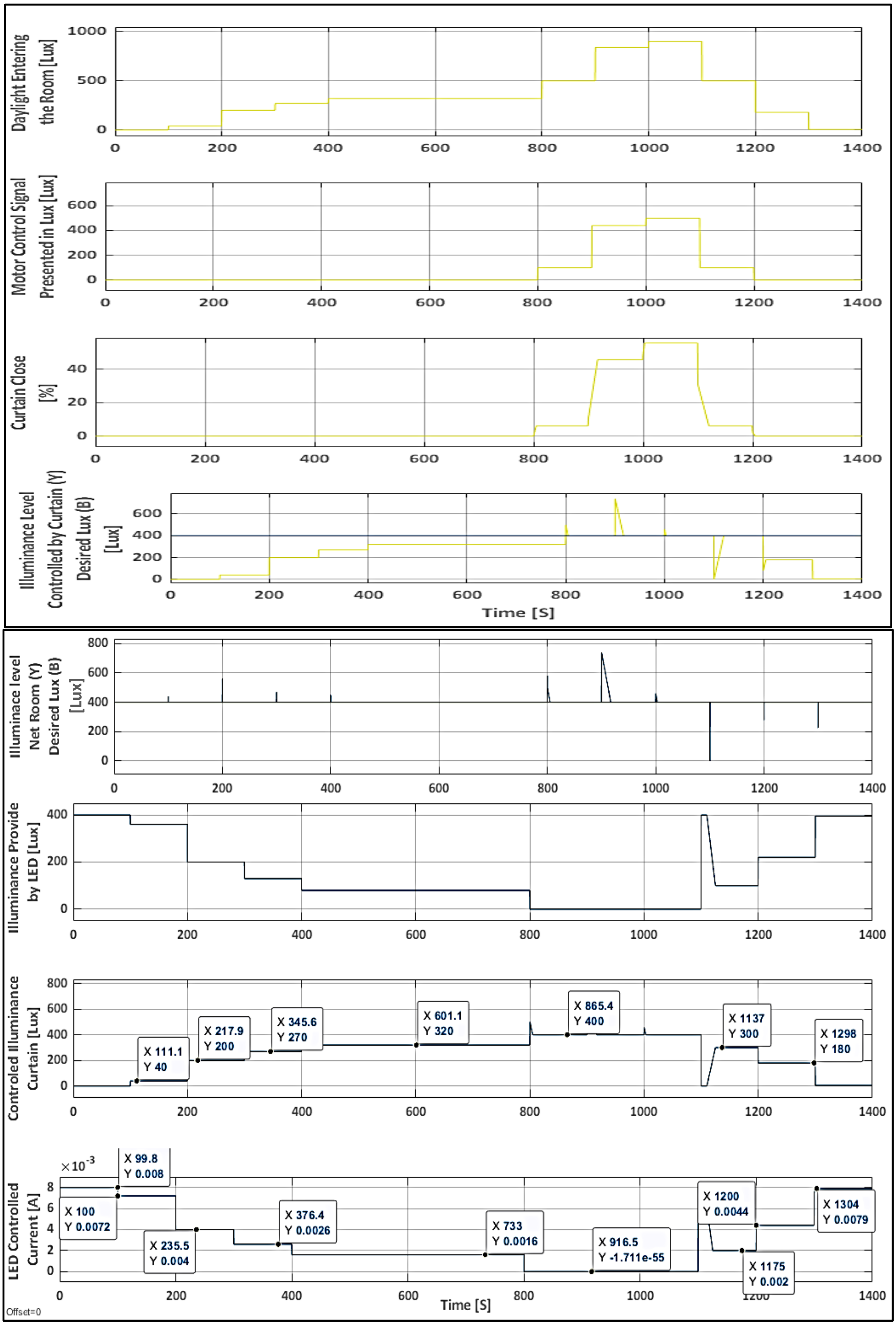

Fig. 9. Lighting operation for 14 hours with a maximum of 900 Lux daylight and a desired illuminance level of 400 Lux.

4.1. Direct Benefit

4.1.1. Power Consumption Saving Percentage

In direct benefit for the indoor lighting of the office using ISLSC, the comparison of the power consumption takes into consideration the illumination of the office with, and without, the ISLSC. Power consumption saving percentage is evaluated from the results obtained in Fig. 9 by calculating the daylight harvesting contribution from area under the "controlled IL by curtain" curve, and refer it to the desired IL calculated from the area under "net controlled IL/ desired IL", ignoring the spics areas, as following:

$$\text{Power Consumption Saving Percentage} = \frac{\text{Daylight Contribution}}{\text{Desired IL}} * 100\% \tag{9}$$

$$= \frac{0 + 40 + 200\ +\ 270\ +\ 4 * 320 + 3 * 400\ +\ 300\ +\ 180\ +\ 0}{14 * 400} = 61.96\ \%$$

Motor power consumption needs to be considered. However, such motor is very small and has fractional HP rating, and whenever it operates the motor will work for few seconds only then it will stop. Also, the occupation sensor can switches-off the complete DHS whenever no body in the room. Therefore, motor consumption is actually negligible compared with the lighting consumption, and it will not be considered in the power consumption calculation.

4.1.2. LED Circuit Maintenance Saving

During operation, LEDs luminous flux gradually decrease due to aging. In general, this aging is affected by different factors such as the operating current, voltage, temperature and humidity. Fig. 10 illustrates the degradation curve of LED light with time [33]. A power LED industry group, the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), found that 70% lumen maintenance is close to the threshold - at which the human eye can detect a reduction in light output driving the LED at a level below its maximum rated forward current – which will extend its useful lifetime, thereby increasing the quotable L70 and L50 lifetimes [34].

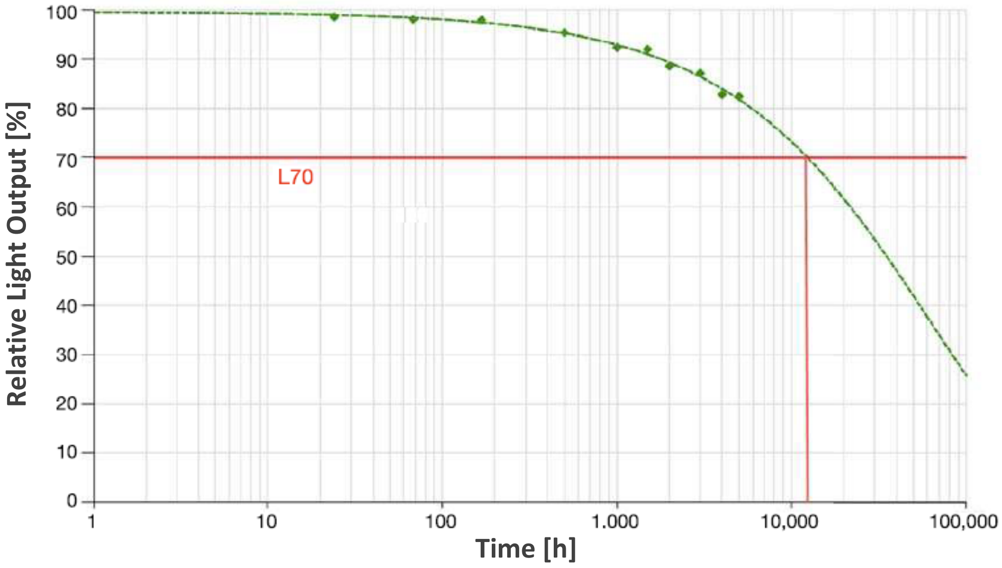

Fig. 10. Lifetime degradation of LED light.

Analyzing the above LED lifetime degradation curve, it can be seen that the LED lifetime can be approximately considered as 12000 hours to give the required luminous flux with satisfaction human eye. Using ISLSC can allow using the same LED fixture with lower luminous flux for some extra time without disturbing the human eye. Fig. 11 illustrates a case study that limits LED luminous flux to 50% for further analysis.

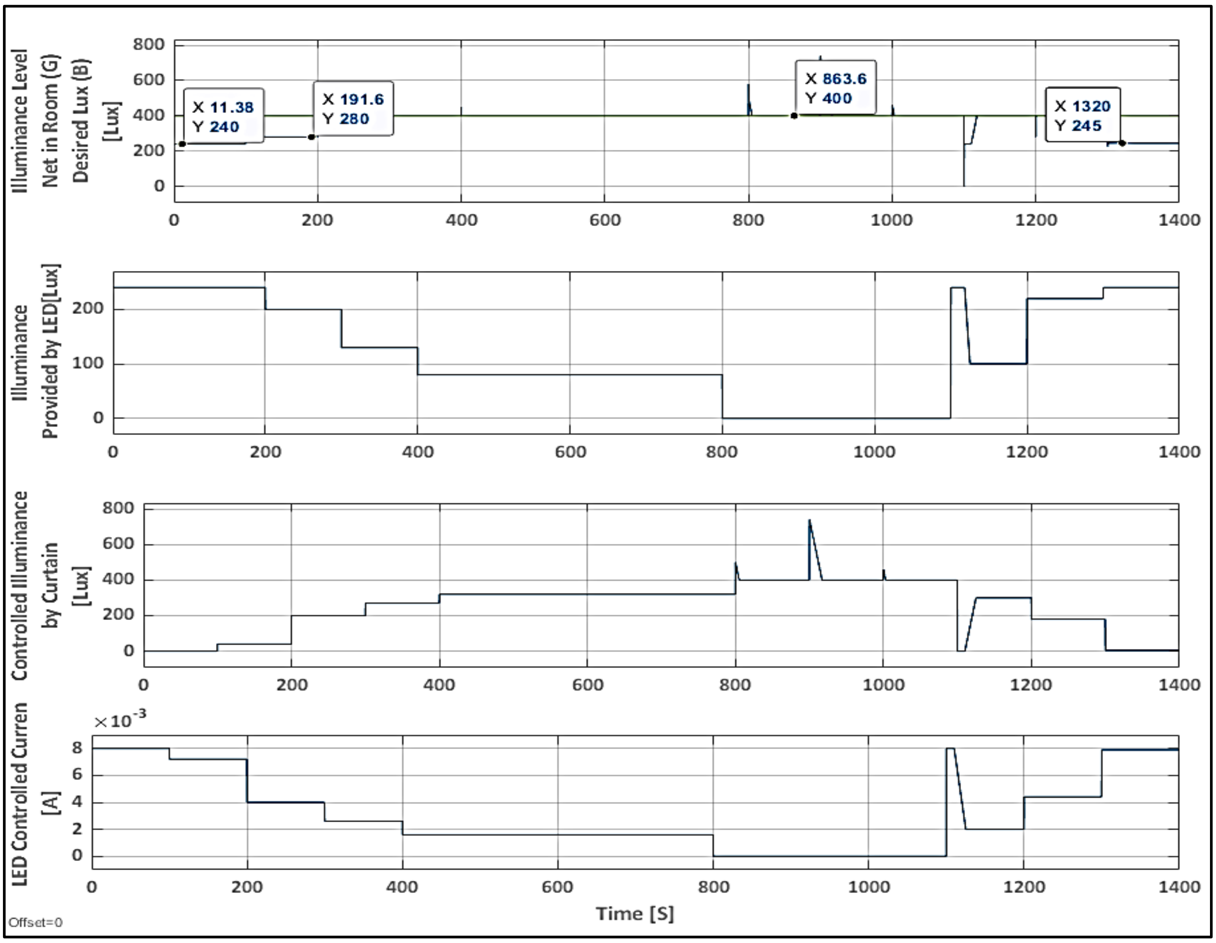

Fig. 11. Lighting operation for 14 hours with 50% of LED luminous flux.

By recalling that the value of the desired lighting intensity for the office is 400 Lux, and 70% of this value is 280 Lux, so, the net IL in the room can go down to 280 Lux without disturbing the human eye. The results of Fig. 11 show that during the office hours from 7:00 am to 9:00 pm, the lighting intensity remains above 280 Lux for 12 hours, and above 200 Lux (50%) for only 2 hours. This result is very acceptable and increases the utilization lifetime of the LED circuits to 300%. This means that the maintenance cost can be reduced by one-third using ISLSC, assuming that the LED circuit is operating at its rated current.

From another direction of the LED lifetime evaluation, as per ASSIST, the temperature of the LED junction also influences lumen maintenance; designing for a lower junction temperature will extend the L70 and L50 figures for the LED. For this reason, thermal design considerations are an important aspect of designing a LED-based lighting system. Accordingly, driving the LED at a level below its maximum rated forward current generates less heat in the LED and hence extends its useful lifetime, thereby increasing the quotable L70 and L50 lifetimes. Fig. 12 illustrates the lifetime of aLED at different loading [33].

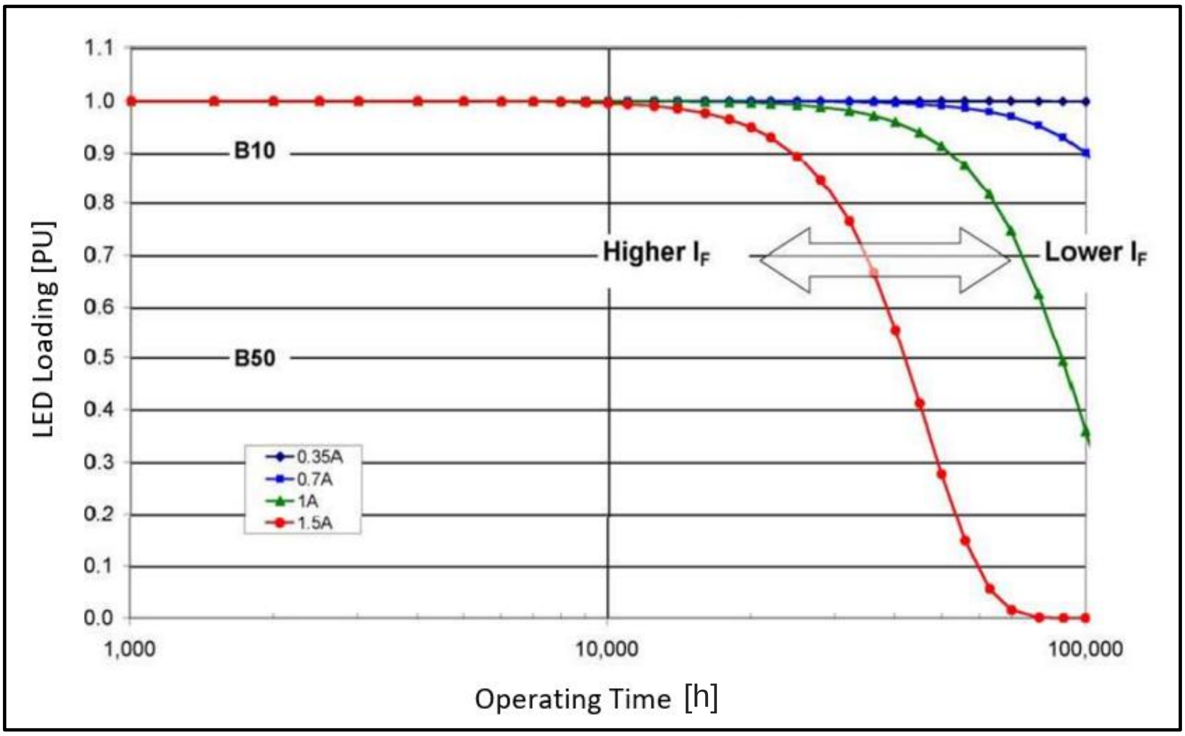

Fig. 12. The effect of forward current value on the useful lifetime of a LED.

To evaluate the LED lifetime due to the operating current reduction, daily average current reduction percentage is calculated using Fig. 11 as following:

$$\text{Daily Average Current Reduction Percentage}$$
$$= 100 - \frac{\text{Average current consumed in 14 Hrs}}{\text{LED full load}} * 100\ \% \qquad (10)$$
$$= 100 - \frac{0.008 + .0072 + 0.004 + 0.0026 + 4 \times 0.0016 + 3 \times 0 + 0.002 + 0.008}{0.008}$$
$$= 65.89\%$$

Using Fig. 12 to estimate the new LED lifetime corresponding to 34.1 % current loading, the graph shows that the LED will have more than 100,000 hours lifetime. This result gives approximately 20 years lifetime for the LED if ISLSC is used.

Based on the above two analyses, using ISLSC - and except of normal cleaning for the light fixtures - the LED circuits will not require any maintenance as long as they are operated within their normal operation conditions.

4.2. Indirect Benefits

4.2.1. Annual Gas Sale Opportunity

By saving the energy consumed in the indoor lighting system using the proposed ISLSC, a country can export larger amount of gas. The average value for gas selling price during the last 25 years is $ 4.17/MBtu on the basis of US Energy Information Administration Henry Hub/NYMEX, natural gas valued spot price [35].

The equivalent energy rate is 0.014228 $/kWhr (thermal) and it is used in Eq. (10) to estimate the annually sales opportunity for the natural gas that can be by obtained by using ISLSC in a building that has 100 standard office with 20 m^2 area each.

Power consumption for one office to achieve 400 Lux from LED circuits is approximately 144 W. Using ISLSC, the saving in power consumption based on the calculated saving percentage value in Eq. (9) is 89.22 W. For 100 office, the total saving in power consumption is 8.922 kW.

For stand-alone gas turbines, the average turbine efficiency is approximately 35% [36]. So the thermal converted saving power is 25.5 kW approximately and the annual energy thermal saving considering 14 hours operating time is 130,262 kWhr (thermal). The annual natural gas sale opportunity is calculated as:

$$\begin{aligned} \mathit{Annual\ Natural\ Gas\ Sale\ Opportunity} &= 0.014228 \times \mathit{Thermal\ Energy\ saving} \\ &= 1{,}853\ \$ \end{aligned} \tag{11}$$

This result is encouraging to install the proposed ISLSC in as many as possible indoor LED circuits to maximize the gas sale opportunity that can be achieved from the reduction of power consumption in indoor lighting.

4.2.2. Annual Saving in Pollution

Second indirect benefit is related to the pollution and hydrocarbon gases emitted from power generation plants to produce electrical power. Carbon credits based on EU Emissions Trading System hit 31 €/ton as in Fig. 13 [37]. CO_2 emission is considered to be 0.83 kg/kWh. Assuming Euro to USD exchange rate of 1.2, by using the proposed ISLSC the annual saving in pollution reduction can be calculated as following [26]:

$$\text{Annual Saving in Pollution} = \frac{0.83 * \text{Thermal Energy saving} * 1.2 * 31}{1000}\,\$ \tag{12}$$

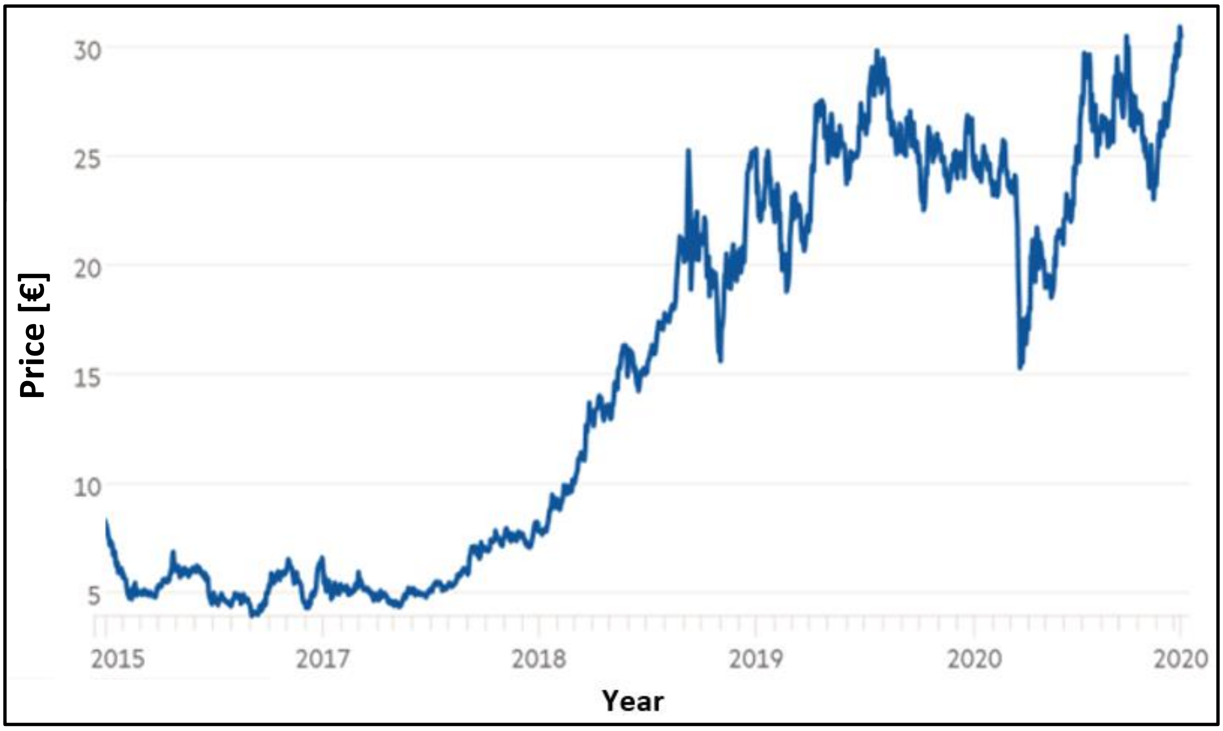

Fig. 13. Carbon credits based on EU emissions trading system.

Thermal energy saving of 130,262 kWhr was calculated for 100 standard office with 20 m^2 area each. This value is used to estimate the annual saving in pollution using Eq. (12). This gives approximately a saving of additional 40,22$ in the indirect benefit.

It is useful to calculate the annual indirect benefit saving index (AIBSI) for standard office as following:

$$\mathrm{AIBSI} = \frac{\text{Annual Natural Gs Sale Opertunity+Annual Saving in Pollution}}{\text{(Number of Offices)}} \tag{13}$$
$$= 58.75\ \$/\mathrm{Office}/\mathrm{Year}$$

This AIBSI index is very encouraging to standardize the proposed ISLSC to be installed with any indoor LED lighting system because of its contribution in global temperature rise solutions. Also, it is important for project managers to use such index to evaluate the cash flow, maintenance requirements and budget decisions.

5. CONCLUSIONS

On average, lighting costs account for one-third to one-half of a building's total electricity costs. Effective daylight harvesting distribution through reflection and diffusion can reduce electric lighting power costs and improve the usefulness of natural light. In this article, efficient ISLSC was proposed to control simultaneously the LED circuit current and the window roller blind position, that is driven by stepper motor, to adjust the indoor lighting intensity to meet the desired IL value. Different test cases were carried out to prove the controller performance precision. The results showed that ISLSC succeeded in maintaining the indoor lighting intensity at the desired IL. The test showed that using ISLSC to control the lighting intensity in different rooms with different daylight conditions, requires only minor calibration, and then the ISLSC will be ready to function under the new condition. Based on this flexibility in the design, the ISLSC can be installed for windows at any of the four directions regardless of the daylight level or its angle. For large rooms with more than one window, additional IL transducer is needed to be fixed at each window that has uncontrolled blind, in order to measure the uncontrolled daylight entering the room to be deducted from the desired IL value.

From the performed techno-economic analysis to calculate the "direct benefit" and "indirect benefit" that can be obtained from the installation of the proposed ISLSC, it was found that in "direct benefit," energy saving of approximately 62 % can be achieved, and the LED circuits lifetime can extend to more than 20 years. "Indirect benefit," saving index was calculated combining the two "indoor benefit" categories in one indictor. "Indirect benefit" index showed saving of 58.75$/Office/Year, this figure is very useful to managers in taking their decisions. Based on this encouraging value, it is recommended - if required - to install the proposed ISLSC in all indoor lighting types - not only for LED circuits - after minor modification.

For future work, artificial intelligent techniques such as artificial neural network or fuzzy logic can be used to design the proposed ISLSC.

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