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# Estimating the switching frequency and energy saving for daylight-linked lighting on-off controls

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**Abstract**

Daylighting is an important and useful strategy for enhancing visual comfort and reducing the electricity consumption by light fittings. In a well day-lit space when the available daylight is far larger than the required level, daylight-linked lighting switching controls can provide substantial energy reductions. However, a drawback with the switching control type is the frequent and swift on and off, annoying occupants and shortening the lamp life. This paper analyses the electric lighting energy reductions and switching frequency of an atrium building under different daylight-linked lighting on-off controls. The results are based on field measurement of daylight illuminance and design implications are discussed.



*Keywords:* daylight-linked lighting controls, Switching, Corridor, differential, time delay;

## 1. Introduction

In most cities, electric lighting represents about 25% of total electricity use in office buildings [1]. Recently, there has been an increasing interest in incorporating daylight in the architectural and building designs to reduce the building energy consumption [2]. Proper uses of daylight such as daylight-linked lighting controls can effectively lower building's energy expenditures, the related greenhouse gases and pollutants emissions. An atrium allows daylight to penetrate into the core of a building, contributing not only cultural and architectural content, but also the potential to

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resolve many environmental aspects. In day-lit corridors, people expect the way ahead to be lit sufficiently and daylight-linked lighting controls can give remarkable lighting energy savings [3]. Basically, there are two basic categories of such lighting controls. The first provides for either on or off state, and the second allows the levels to be set between the maximum and minimum levels by dimming. In general, dimming controls can reduce more lighting energy use than on-off controls particularly at high target illuminance settings [4]. In a well daylit space or low design illuminance levels when available daylight intensities are always larger than the target illuminance settings, the energy savings from on-off controls can be more than those from the dimming lighting controls [5]. However, a blemish with the switching control type is the frequent switching which annoys occupants and lowers the light fitting life [6]. It is also essential to visual comfort, building energy and cost issues. Daylighting design approaches are often demonstrated through field measurements to give actual operational data for establishing design strategies [7]. Previously, we analyzed the electric lighting energy savings and switching frequency for a number of daylight-linked lighting on-off controls [8]. This paper extends to the approach to more day-lit spaces and discusses the design implications.

## 2. Daylight-linked lighting controls

An on-off control is designed to switch electrical lighting on and off automatically as the lighting levels go up and drop within a set of predetermined values. The daylight illuminance recorded by a photocell at each time was checked and if this was less than the target illuminance ($E_t$), the control would keep the lights on since the last scan. If it was larger than the $E_t$, the lights would be turned off. A special demerit with the on-off lighting controls is rapid switching, particularly during unsteady sky conditions when the daylight changes around the target illuminance level. This can disturb users and reduce light fitting life. There are several variants of the standard on-off control to limit the number of on and off [9]. The fundamental one is the ‘differential switching or dead-band’ photoelectric control which includes two switching illuminance levels: one at which the lights are turned on ($E_{on}$), and another of higher illuminance, at which the lights are turned off ($E_{off}$). The main merit is that it can lower the quick switching on and off when the illuminance oscillated around the required value. Moreover, it makes lamps shutting down less obtrusive, as it is carried out when daylight stands for a larger proportion of the illuminance to which the eye is adapted. Another approach to lower the number of on and off is to apply a time delay into the operation. Two types of time delay viz. switching-linked and daylight-linked time delays are studied. The switching-linked time delay only permits switching off until the preset delay had to pass after the previous switch on. For daylight linked time delay, the lighting could only be switched off when the daylight illuminance had surpassed the target value for the preset time period. Delay in switching on is not considered as it could lead to illuminances dropping well below desired levels.

## 3. Data availability

The daylight illuminance data for analysis were measured in an institutional building consisting of a 13-storey block located in Hong Kong, at a latitude of 22.3N and a longitude of 114.2E. The building was designed with a skylight and an enclosed, stepped atrium to harvest daylight. The stepped atrium strengthens daylight and enhances sky views by splaying the well walls away from the vertical, but the sky component and hence the daylight factor of the lower floors are substantially lowered [10]. The atrium dimensions are 11.5 m $\times$9.5 m $\times$ 40.7m (height). The lower part of the atrium between 2/F and 9/F are typical classrooms, with four open corridors surrounding the atrium. The upper parts of the atrium between 10/F and 13/F, is a cubic atrium containing mainly mechanical rooms and office spaces. The atrium corridors are used for circulation among different classrooms, with dimensions of 2.65 m$\times$14.65 m $\times$2.22 m (height). There were 67 ceiling-mounted energy-efficient T5 fluorescent tubes, with rated power ranging between 14 W and 35 W. The peak lighting load is 2261W including electronic ballast load. The lighting power density, defined as the electrical power consumed by lighting installations per unit floor area in the corridor, is 14.6 W/㎡.

The daylight illuminance data were recorded at 2.5-min intervals, daily, from 9:00 am to 6:00 pm between January 2012 and September 2014. Setting aside any missing data including instrumentation malfunction and power failure, totally around 630,000 data (4 zones at 9/F) were collected for analysis. At the end of the working day, the percentage of time the lights off was calculated. The number of switch offs was computed by keeping a record of the control changed state and the turn off at the end of the day was rejected in the totals. For all the control strategies examined, if at 9:00 the daylight illuminance was above the switching on illuminance then the lighting was assumed to be turned off at the beginning. If the day just has only once turning off, no switching will be counted for that nday. It was assumed that the measured illuminance values were kept unchanged within the whole of the time interval of 2.5 minutes.

The daylight availability is the key variable to indicate the percentage of the working year in which a given illuminance is exceeded. Fig. 1 displays the cumulative frequency distributions for the daylight illuminance data for Zones 1, 2, 3 and 4 of 9$^{th}$ floor at an interval of 50 lux. It can be seen that relatively large percentage were collected at low illuminance of 300 lux or less. The percentage dropped gradually from low to high illuminance, indicating a decreasing trend for the 4 zones. For all setting illuminance values, Zone 4 scored the largest frequency, Zone 2 the second, Zone 1 the third and Zone 3 the fourth. For high illuminance, the discrepancies are very significant. For instance, at 500 lx, the frequencies for Zones 1, 2, 3 and 4 are observed to be 27, 34, 12 and 47%, respectively.

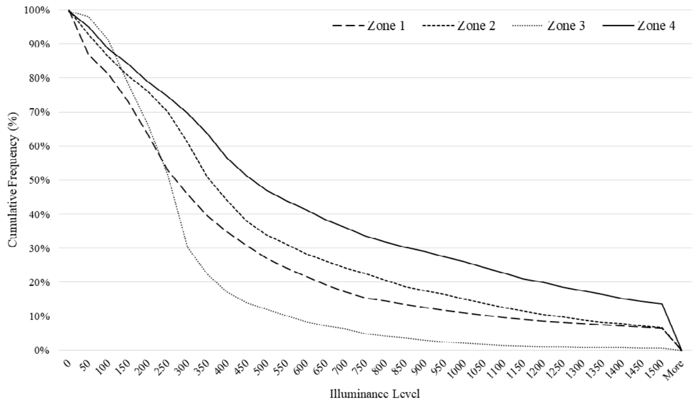


Fig. 1. Cumulative frequencies of the indoor daylight availability for 4 zones at 9/F

## 4. Measured results and analysis

There were three switching illuminance of 200, 225 and 250 lux using the standard switching control. For differential switching controls, at target illuminance of $E_{on}$=200 lux was considered and $E_{off}$ =210, 220, 250, 280 and 300 lux were examined. Table 1 summaries the range and the average number of switch offs per day and the percentage of working day (9:00-18:00) that the lights are switched off at the four zones in 9/F under the standard switching control and differential switching controls. The recorded minimum number of switch offs per day was zero for all cases but the maximum number of switch offs can be up to 26 which imply at least 51 switching operations in a day if switch ons are also included. Such a large number of switching operations could result in remarkable annoyance to occupants. The average number of switch offs per day ranged between 3.5 and 10.3. When switching illuminance was at 200 lux, the percentage of lighting energy savings were 64%, 76%, 67% and 79% at Zones1, 2, 3 and 4, respectively. It shows that the lighting energy saving was quite good but the switching number was not acceptable. The number of switch offs was considerably decreased using differential switching controls. The recorded maximum number of switch offs was 21 at Zone 1 when $E_{off}$ =210. When the $E_{off}$ =300 lux the average numbers of switch offs were 3.7, 2.3, 2.4 and 1.6 at Zones 1, 2, 3 and 4, respectively. However, the lighting energy savings of differential switching controls were less than those under standard switching controls. As mentioned, the electric lighting energy under the differential switching control can be considered as the fraction of the working year of the mean values of $E_{on}$ and $E_{off}$ ($E_{mean}$). When the $E_{mean}$=205 lux (i.e. $E_{on}$=200 lux and $E_{off}$ =210 lux) the simulated lighting energy saving was around 2% less than when $E_t$=200 lux under the standard on-off control. The same results can be observed for other two switching illuminances ($E_t$=225 lux and $E_t$=250 lux). The findings were in good agreement with other independent studies [9].

Switching- and daylight-linked time delay switching controls were examined. For individual control type, six different time delays from 5 up to 60 min at switching illuminance of 200 lux were applied. Table 2 shows the daily average number of switch offs and the percentage of working day that the lights are switched off for respectively switching and daylight-linked time delay controls. A short time delay (e.g. 10 and 15 min) gives a reduction in switching particularly for the daylight linked time delay control. The maximum switch offs of time delay controls were less than those using the differential control. It shows that time delay controls give a smaller variation on number of switching. The number of switch offs drops with longer time delay but the light energy savings also decreases particularly for an hour delay, ranging from 49% to 79% for the four zones. Based on the results shown in the tables, daylight linked time delay has the lowest number of switching for the same percentage of lighting energy savings. It means that daylight-linked time delay performed better than switching-linked time delay in terms of the number of switch offs.

Table 1. Under standard switching controls and differential switching controls

| Standard switching controls | Control switching illuminance(lux) | | | | Differential switching controls | | Control switching illuminance(lux) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 200 | 225 | 250 | | | 200/ 210 | 200/ 220 | 200/ 250 | 200/ 280 | 200/ 300 |
| Zone 1 | Range | 0-23 | 0-26 | 0-25 | Zone 1 | Range | 0-21 | 0-20 | 0-17 | 0-13 | 0-12 |
| | Average number | 7.9 | 9.2 | 9.1 | | Average number | 7.3 | 6.6 | 4.9 | 4.0 | 3.7 |
| | % of working day | 64% | 59% | 54% | | % of working day | 63% | 62% | 58% | 57% | 53% |
| Zone 2 | Range | 0-16 | 0-17 | 0-19 | Zone 2 | Range | 0-14 | 0-13 | 0-11 | 0-9 | 0-7 |
| | Average number | 3.9 | 4.9 | 6.4 | | Average number | 3.5 | 3.2 | 2.7 | 2.5 | 2.3 |
| | % of working day | 76 % | 73% | 70% | | % of working day | 75% | 75% | 71% | 73% | 70% |
| Zone 3 | Range | 0-21 | 0-23 | 0-24 | Zone 3 | Range | 0-18 | 0-15 | 0-13 | 0-12 | 0-10 |
| | Average number | 6.3 | 8.2 | 10.3 | | Average number | 5.3 | 4.6 | 3.4 | 3.0 | 2.4 |
| | % of working day | 67% | 60% | 53% | | % of working day | 65% | 64% | 59% | 57% | 50% |
| Zone 4 | Range | 0-17 | 0-16 | 0-14 | Zone 4 | Range | 0-15 | 0-12 | 0-7 | 0-6 | 0-5 |
| | Average number | 3.9 | 3.7 | 3.5 | | Average number | 3.7 | 3.0 | 2.3 | 1.9 | 1.6 |
| | % of working day | 79% | 76% | 74% | | % of working day | 78% | 77% | 74% | 75% | 71% |

Table 2. Under switching and daylight linked time delay controls at switching illuminance of 200 lux

| Switching linked time delay controls | | | | Time delay (minutes) | | | Daylight linked time delay controls | | | | Time delay (minutes) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zone | | 5 | 10 | 15 | 30 | 60 | Zone | | 5 | 10 | 15 | 30 | 60 |
| 1 | Range | 0-16 | 0-15 | 0-15 | 0-14 | 0-13 | 1 | Range | 0-12 | 0-10 | 0-6 | 0-4 | 0-3 |
| | Average number | 5.8 | 5.7 | 5.6 | 5.4 | 5.2 | | Average number | 3.7 | 2.7 | 2.2 | 1.4 | 0.9 |
| | % of working day | 68% | 67% | 66% | 64% | 61% | | % of working day | 65% | 64% | 59% | 55% | 49% |
| 2 | Range | 0-8 | 0-9 | 0-8 | 0-8 | 0-8 | 2 | Range | 0-8 | 0-6 | 0-5 | 0-3 | 0-2 |
| | Average number | 2.9 | 2.8 | 2.8 | 2.7 | 2.7 | | Average number | 2.1 | 1.6 | 1.3 | 1.1 | 0.9 |
| | % of working day | 79% | 78% | 78% | 77% | 75% | | % of working day | 77% | 76% | 74% | 70% | 65% |
| 3 | Range | 0-16 | 0-15 | 0-13 | 0-13 | 0-12 | 3 | Range | 0-10 | 0-9 | 0-7 | 0-4 | 0-3 |
| | Average number | 5.5 | 5.1 | 4.8 | 4.6 | 4.4 | | Average number | 3.0 | 2.3 | 1.8 | 1.4 | 1.0 |
| | % of working day | 70% | 70% | 69% | 67% | 65% | | % of working day | 69% | 66% | 64% | 59% | 53% |
| 4 | Range | 0-11 | 0-10 | 0-10 | 0-11 | 0-10 | 4 | Range | 0-6 | 0-5 | 0-4 | 0-3 | 0-2 |
| | Average number | 3.0 | 2.9 | 2.7 | 2.6 | 2.5 | | Average number | 1.8 | 1.4 | 1.2 | 0.9 | 0.8 |
| | % of working day | 82% | 81% | 81% | 80% | 79% | | % of working day | 80% | 79% | 77% | 74% | 69% |

The electric lighting energy savings under various daylight linked on and off controls strongly relate to the corresponding number of switching. As seen the data in the Tables 1 and 2, smaller number of switch offs giving less lighting energy savings and vice versa. Figures 2 to 4 display the correlations between the percentage savings and average number of switch offs per day at Zone 2 under the three variants control types (i.e. differential switching,

switching-linked and daylight-linked time delays). The scatter of data points in the figures can be explained by the variety of energy savings for different switching off numbers. Through regression techniques, three simple mathematical expressions to correlate the average switch offs per day (N) with the lighting energy saving (LES) at Zone 2 were formulated.

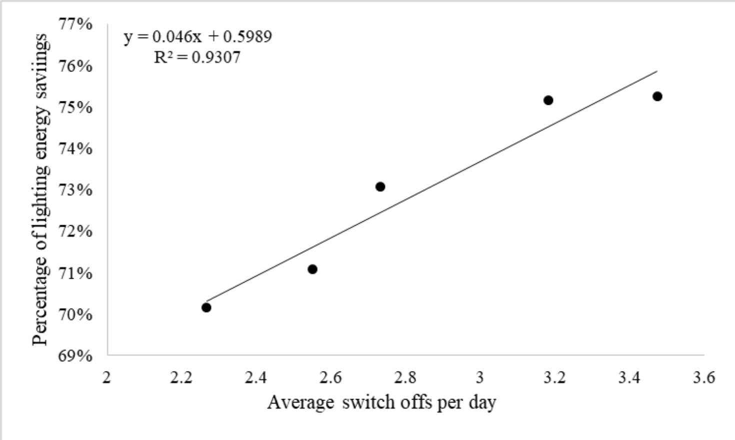


Fig.2. Correlation between lighting energy savings and average switch offs using differential switching controls.

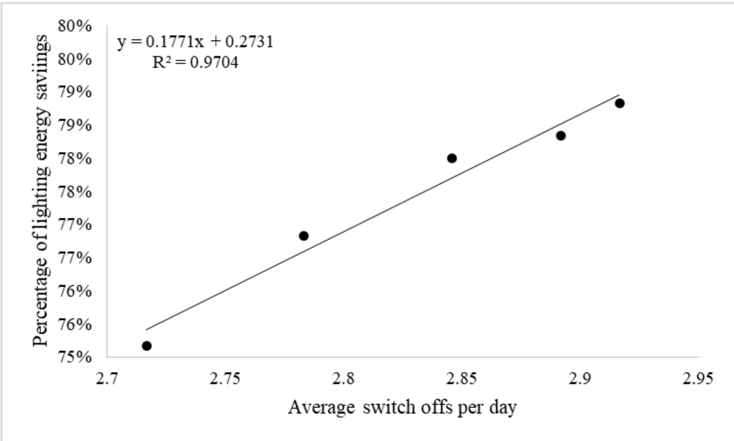


Fig.3. Correlation between lighting energy savings and average switch offs using switching-linked time delay controls.

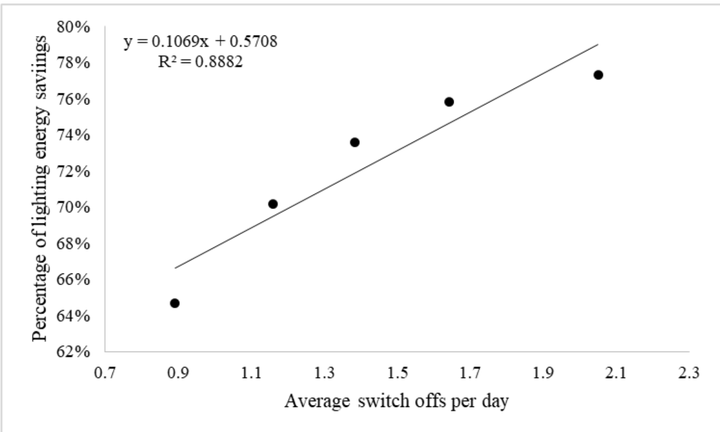


Fig.4. Correlation between lighting energy savings and average switch offs using daylight-linked time delay controls

LES = 0.046 N + 0.6 $R^2 = 0.93$ (differential switching controls) (1)
LES = 0177 N + 0.273 $R^2 = 0.97$ (switching-linked time delay controls) (2)
LES = 0.107 N + 0.571 $R^2 = 0.89$ (daylight-linked time delay controls) (3)

Equations 1 to 3 have large coefficients of determination ($R^2$), ranging between 0.89 and 0.97. It shows that 89-97% of the variations in percentage of lighting energy savings can be explained by the variations in the average number of switch offs. The strength of correlation is thus considered very strong. The mathematical expressions can give an alternative to predict electric lighting energy saving from a particular number of switch offs under different daylight linked switching controls such that the most suitable type can be adopted.

## 5. Conclusions and future work

Daylight-linked lighting on-off controls can lower electric lighting energy use by switching off the light fittings when daylight illuminance is adequate. However, a disadvantage with such control is the frequent switching on and off which would annoy occupants and shortening the lamp life. The appropriate strategy should be a low number of switching off with a large energy saving. On-site measurements of the daylight illuminance in atrium corridors were conducted. With the measured daylight data, a number of daylight linked switching controls viz. the standard, differential, switching-time and daylight-time delays were examined. Their performances in terms of lighting energy saving and number of switching were estimated and analyzed. Under the simple switching control, the energy saving was very good but the frequent switching was quite large. At the switching illuminance of 200 lux, the lighting energy savings were calculated ranging between 64% and 79% and the average number of switch offs from 3.9 to 7.9. Referring to the simulated results, the variants of the switching control can lower the number of on and off but increase the energy expenditure. Based on the differential switching control, the number of switch offs can be decreased to 1.6 with an energy saving of 71% at Zone 4 when $E_{on}$ = 200 lux and $E_{off}$ = 300 lux. The switching and daylight linked time delay controls were studied. Given an appropriate delay time is selected, a daylight linked time delay can give less number of switch offs with smaller energy savings. The correlation between the percentage of lighting energy savings and the number of switch offs was studied. Three simple mathematical expressions for the three control types at Zone 2 were developed. The findings can give an approach to calculate the electric energy savings from the chosen number of switch offs based on the various daylight-linked lighting on-off controls. The important issue would be whether the number of switch offs can be achieved by a particular switching control. Photoelectric electric lighting controls are appropriate building energy conservation strategies and should therefore be widely applied in day-lit areas.

The performance of individual daylight-linked lighting on-off controls strongly reply on the interior daylight availability which is important for architectural and daylighting designs. Further research work is required to fit the approach for various daylighting criteria such as the cumulative frequencies of the daylight availabilities in various indoor day-lit spaces and daylight factor under different sky conditions.

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