LBL-18065

To be presented at the IEEE Industry Applications
Society Annual Meeting, Chicago, IL,
September 30 - October 4, 1984

THE CONTROL OF DAYLIGHT-LINKED LIGHTING SYSTEMS

F.M. Rubinstein and G. Ward

June 1984

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-18065
EEB-L 84-08
L-90

To be presented at the IEEE Industry Applications Society Annual Meeting, Chicago IL, September 30-October 4, 1984.

THE CONTROL OF DAYLIGHT-LINKED LIGHTING SYSTEMS

F.M. Rubinstein and G. Ward

Lighting Systems Research Group
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720 U.S.A.

June 1984

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

THE CONTROL OF DAYLIGHT-LINKED LIGHTING SYSTEMS

Francis Rubinstein and Gregory Ward
Lighting Systems Research
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

Abstract: This paper describes the components of a daylight-linked lighting system and presents three simple control algorithms that can be incorporated into a control system to achieve the design objective of constant task illuminance.

Introduction

In buildings where daylight can serve as a useful source of illumination, photo-electric controls can significantly reduce electric lighting energy consumption [1-4]. Generally, the design objective of such control systems is assumed to be the maintenance of a total level of illumination (available daylight plus supplied electric light) at the task surface equal to (or perhaps exceeding) the design light level. This paper describes the major components of a photo-electric dimming system and presents three simple control algorithms that can be incorporated into a control system to achieve the design objective.

System Components

Any photo-electrically controlled lighting system can be considered to consist of three basic components:

- A photosensor for measuring the light level within (or possibly exterior to) the controlled space. The photosensor (typically a silicon photodiode in a small housing) generates an electric signal in proportion to the illumination striking it.
- A controller that uses a built-in control algorithm to transform the photosensor signal into a control signal that drives the dimming unit.
- A dimming unit that smoothly varies the output of the electric lights. The dimming unit can range in size from a large centralized unit capable of controlling the output of all the lights on a branch circuit to an electronic ballast capable of individual lamp control.

Although the way in which the above elements are combined will depend on the specific system and application, all photo-electric controls incorporate these elements in some fashion.

Figure 1 shows how the different control system components are interconnected and illustrates a typical mounting configuration for the control photosensor. In this configuration (with the photosensor mounted in the ceiling of the controlled space), the photosensor is susceptible to the (controlled) electric light as well as to daylight.

Nomenclature

The following nomenclature is defined:

$S_T(t)$ = signal produced by photosensor (time-dependent).

$S_D(t)$ = daylight component of $S_T(t)$.

$S_E(t)$ = electric light component of $S_T(t)$.

δ = fractional output of electric lights ($0 \leq \delta \leq 1$). Full light output, $\delta = 1$.

I_{Em} = task illuminance level for $\delta = 1$ without daylight.

S_{Em} = signal produced by photosensor for $\delta = 1$ without daylight.

$I_D(t)$ = daylight at task (time-dependent).

$I_E(t)$ = electric light at task (time-dependent).

$I_D(t)$, $I_E(t)$, and I_{Em} as defined above refer to the particular point at the task surface where the design objective is to be satisfied.

Controller

This paper focuses on the operation of the controller, which determines how much electric light to supply based on the information obtained from the photosensor. It is not necessary to consider the internal workings of the controller in order to understand what the controller does. Rather, the controller is treated simply as a black box: one need consider only how the controller transforms its input, the photosensor signal, into an output, the control signal that drives the dimmer. Selecting the specific functional form of this transformation, i.e. the control algorithm, is a fundamental circuit design decision. If the design objective of constant task illuminance is to be achieved, the control algorithm must properly account for the location of the photosensor relative to the work plane and the light sources in the space.

There are three simple control algorithms that can be easily designed into a control system. These are termed here the a) constant set-point b) sliding set-point and c) open-loop proportional control algorithms. If the photosensor is located as shown in Fig. 1, i.e. susceptible to the electric light which it controls, (closed-loop control), then the constant or sliding set-point algorithms would be used. If, on the other hand, the photosensor is located outside the controlled space so that it can detect only daylight (or inside but shielded from electric light) then the system should use the open-loop proportional control algorithm.

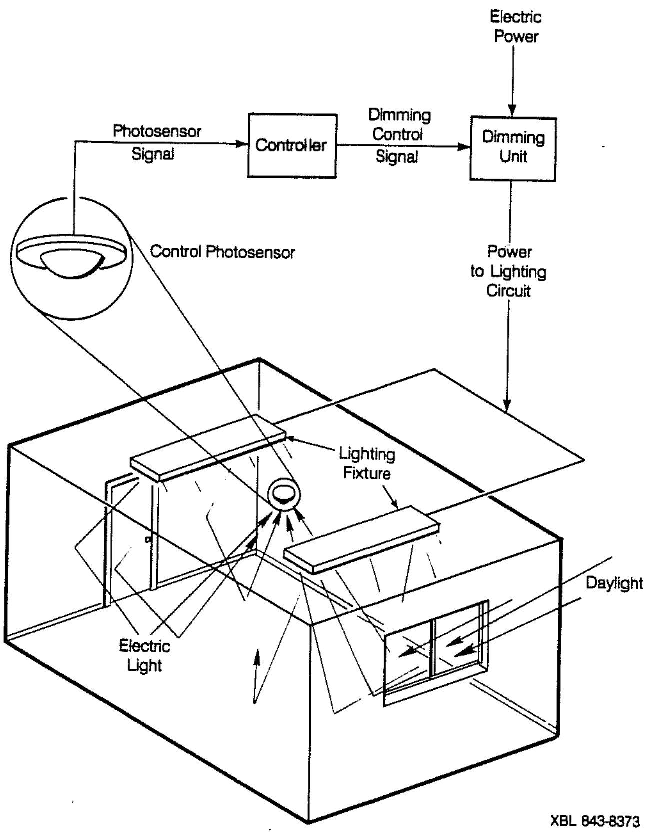

Figure 1. Schematic representation showing the relationship between the components of a photo-electric dimming system in a typical building application. The ceiling-mounted photosensor shown here is sensitive to electric light within the space as well as daylight.

Constant set-point

A constant set-point system simply compares the instantaneous photosensor signal, $S_T(t)$, to a pre-set reference level (typically S_{Em}) and adjusts the light output, δ, to null the difference. In other words, the system continually adjusts the light output in such a manner that the measured photosensor signal does not deviate from the reference level. Figure 2 shows the relationship between the total photosensor signal and the fractional light output for a system that obeys this algorithm. Note that δ is not a function of S_T since the fractional dimming level takes on all values between 0 and 1 for one value of S_T. Also shown in Fig. 2 is the response of the electric lighting system as a function of the daylight component, S_D. As S_D approaches S_{Em} (the reference level determined by calibrating the lighting control system at night as described below), the lights are reduced to minimum. Conversely, as the daylight component approaches zero, the lights will go to full intensity. It should be realized that the control system does not detect the daylight component alone, but rather maintains the sum of S_D and S_E constant (by adjusting S_E through δ). Nonetheless, illustrating the response of the control system as a function of daylight component is useful for understanding how the independent variable, daylight, affects control system response. Note that the slope of the daylight response curve is $-\frac{1}{S_{Em}}$ and is not related to the spatial distribution of daylight.

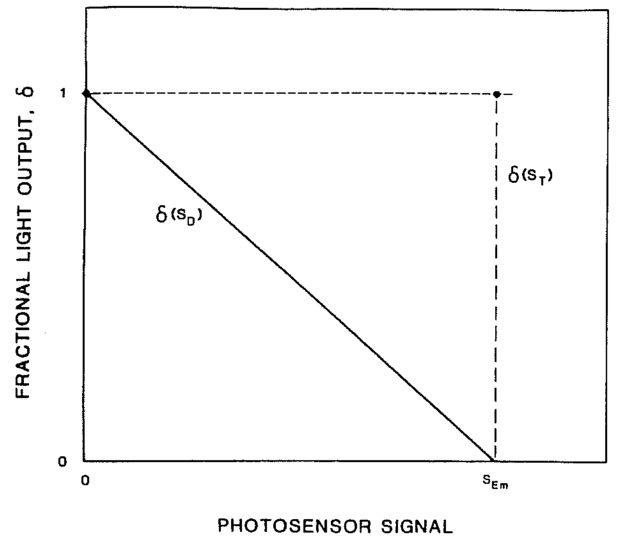

Figure 2. Relationship between fractional light output and total photosensor signal ($\delta(S_T)$) for system using constant set-point algorithm. Solid line ($\delta(S_D)$) shows response of system to daylight component.

Open-loop proportional control

Open-loop proportional control can be used only with a photosensor that is mounted so as to be insensitive to electric light. As shown in Fig. 3, the function $\delta(S_D)$ is trivially identical to $\delta(S_T)$ because $S_D = S_T$. As S_T increases, the lights dim proportionally. However, there is no feedback in the control of δ. The relative change in fractional light output for a given change in photosensor signal is determined by the prevailing daylight conditions during the time of calibration (t_c). The slope of the daylight response line shown in Fig. 3 assumes that the system was calibrated so as to provide a total light level of I_{Em} at a time t_c during the day (calibration procedures are discussed below). In the absence of daylight, the signal from the photosensor will be zero.

Sliding set-point

The response of a closed-loop system obeying the sliding set-point algorithm is shown in Fig. 4. The slope of the daylight response line shown here assumes, as in the open-loop case, that the system was calibrated to provide a total light level of I_{Em} at a time t_c during the day. One major difference between the sliding set-point system and the open-loop algorithm is in the relationship between the total photosensor signal and the fractional light output, δ. In particular, the photosensor signal for a sliding set-point system will not be zero when there is no daylight because the photosensor will continue to generate a signal due to the electric light component. Thus, the sliding set-point approach requires a nighttime calibration in addition to the daytime calibra-

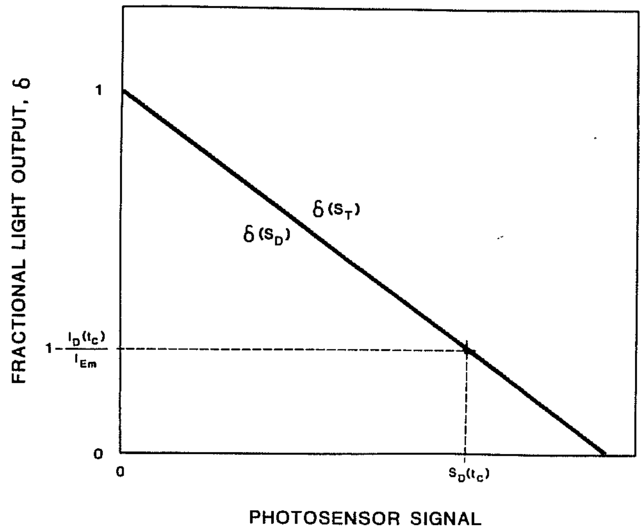

Figure 3. System response to photosensor signal for system using open-loop proportional control algorithm.

tion to set the system response for zero daylight conditions. (The system response illustrated in Fig. 4 assumes that the system is calibrated to provide full light output at night, which is typically the case). Another major difference between the sliding set-point algorithm and open-loop proportional control is that feedback is used in the sliding set-point system. Because of the presence of feedback, the sliding set-point system is able to measure not only the daylight striking the photosensor but also the system's response to this stimulus. Inspection of Figs. 2-4 indicates that the sliding set-point system contains features of both the other control algorithms; in fact, it will be noted that constant set-point and open-loop proportional control are special cases of the more general sliding set-point solution.

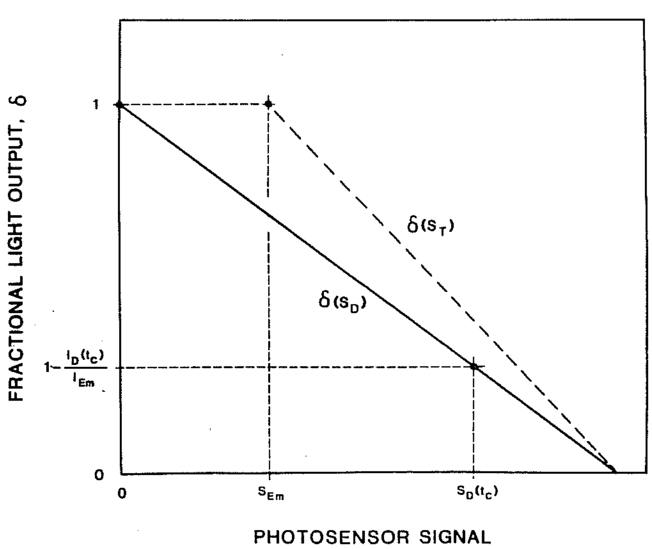

Figure 4. Relationship between fractional light output and total photosensor signal ($\delta(S_T)$) for system using sliding set-point algorithm. Solid line ($\delta(S_D)$) shows response of system to daylight component.

Calibration

After a photo-electric control system is installed at a job site and the interior furnishings are in place, the system response must be calibrated to the particular space conditions. As previously noted, constant or sliding set-point systems must be calibrated at night and open-loop and sliding set-point systems must be calibrated during the day.

The purpose of the nighttime calibration is to establish the reference level or voltage against which the closed-loop photosensor signal will be compared during daytime operation. Typically, the calibration is performed with the electric lights set to maximum output. A simple potentiometer adjustment then establishes the photosensor voltage produced under these conditions as the reference level (S_{Em} in Figs. 2 and 4).

Calibration of open-loop and sliding set-point systems during the day is, of course, more complicated than the nighttime calibration described above because the daylight phenomenon is inherently time-dependent. In selecting the time, t_c, at which to perform the daytime calibration, the following guidelines generally apply:

- If possible, the calibration should be done when the sun is shining (i.e., not blocked by clouds).
- The contribution of daylight to the illuminance at the task surface at t_c should be sufficiently large that electric lights can be significantly but not fully dimmed.

Once the appropriate daytime condition is selected, a photometer is placed at the task surface, and the potentiometer that controls the slope of the photosensor response is adjusted until the total illuminance (daylight plus electric light) equals the desired level (generally equal to or possibly somewhat exceeding the light level supplied by full electric lighting at night). This calibration must be performed once in each individually controlled space. However, if done correctly, adjustments should be necessary only if the room furnishings change significantly.

Discussion and Conclusion

A quantitative analysis of the differences between the three control algorithms and their suitability relative to the design objective (maintaining a constant level of illumination at the task surface under various daylight conditions) is beyond the scope of this paper. Some qualitative features can be outlined, however.

A constant set-point system is calibrated only at night; it follows that this system will be able to satisfy the design objective only if the ratio between the photosensor signal and the light at the task is the same for the daylight component as for the electric light component. As suggested in [5], this condition will not be satisfied in most daylighted spaces unless the photosensor is mounted at the task surface. Since this is rarely desirable, one must conclude that the constant set-point algorithm is poorly suited to achieving the design objective.

Because the open-loop and sliding set-point systems are both daytime-calibrated to provide the desired task illuminance level at time t_c, it follows that these systems should be able to meet the design objective as long as the relative spatial distribution of daylight in the room remains constant. The degree to which this condition is satisfied in most daylighting applications is one objective of our current research efforts.

Acknowlegdement

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

1 D.R.G. Hunt and V.H.C. Crisp, "Lighting Controls: Their Current Use and Possible Improvement," International Journal of Energy Research, vol. 2, no. 4, pp. 343-374, 1978.

2 A. Levy, "Lighting Controls, Patterns of Lighting Consumption, and Energy Conservation," IEEE Transactions on Industry Applications, vol. IA-16, no. 3, pp. 419-427, 1980.

3 F. Rubinstein and M. Karayel, "The Measured Energy Savings from Two Lighting Control Strategies," Conference Record of the IEEE Industry Applications Society Annual Meeting, pp. 1342-1349, 1982.

4 V.H.C Crisp, "Energy Conservation in Buildings: A Preliminary Study of the Use of Automatic Daylight Control of Artificial Lighting," Lighting Research & Technology, vol. 9, no. 1, pp. 31-41, 1977.

5 F. Rubinstein, "Photo-Electric Control of Equi-Illumination Lighting Systems," General Proceedings of the 1983 International Daylighting Conference, pp. 373-375, 1983.