Lighting Systems Control for Demand Response

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***Abstract*—Lighting is a major part of energy consumption in buildings. Lighting systems will thus be one of the important component systems of a smart grid for dynamic load management services like demand response. We consider the problem of control of multiple lighting systems in a building for providing demand response service. In the scenario considered in this paper, under a demand response request, lighting systems in a building react by executing dimming control to reduce power consumption based on their load shedding flexibilities. Load shedding flexibility reflects the amount of power reduction that can be achieved by an individual controller without violating minimum illumination requirements of occupants in that area. We consider different methods for distributing load reduction across the multiple lighting system controllers employing their respective load shedding flexibilities. The performance of the methods is compared with a scheme where uniform dimming is applied across the lighting systems.**

I. INTRODUCTION

Electrical power infrastructure is undergoing major changes driven by regulatory efforts towards reducing energy consumption and by the availability of relevant technologies. The resulting *smart grid* [1] is envisioned to have connected loads, generation facilities and renewable energy sources tied together by communication and control means. Dynamic load management in order to match electricity generation and transmission/usage in such a smart grid becomes increasingly relevant and challenging [2]. Load management techniques like demand response have been found to significantly contribute to peak load reduction [3], [4]. In this paper, we consider demand response achieved via control of lighting systems in buildings.

Lighting systems are reported to consume 20-35% of the energy used in buildings [5, Table E1], and 38% of the used electricity, more than any other end use [5, Table E3]. Lighting systems thus have an interesting potential for load management. With the advent of easily and accurately dimmable sources such as light emitting diodes (LEDs), lighting systems have become attractive as controllable loads to offer dynamic load management services such as demand response. This is further facilitated by increasingly embedded sensing, communication and control functionalities in lighting systems. In particular, the scoping study on demand responsive lighting in [6] identifies market drivers and technology trends like dimming ballasts and communication technologies in buildings that can improve the demand responsiveness of commercial building lighting systems. It quantifies the potential energy savings when implementing demand response control strategies and the associated environmental benefits with the state of California as a case study.

In this paper, we consider multiple lighting systems in a building whose electrical infrastructure can communicate with the smart grid (via a smart utility meter, for instance). A demand response request may be made via the utility meter which in turn is connected to the building management system. This system manages the multiple group controllers corresponding to the lighting systems. A lighting system comprises of one or more light sources, which are controlled by the group controller. Each group controller determines the dimming levels of its associated light sources. We are interested in the problem of load reduction distribution across the lighting systems under a demand response request. We first introduce the notion of load shedding flexibility, which is the amount of power reduction a group controller can offer while respecting the illumination requirements on the associated lighting system. We seek to achieve load reduction distributions while taking into account the different load shedding flexibilities. Based on two different criteria, we develop control algorithms to achieve the desired load reductions.

The paper is structured as follows. In Section II, we describe current methods for lighting control for demand response and discuss some of their disadvantages. In Section III, we describe the set-up of a lighting system and introduce the idea behind load shedding flexibility, that describes per area the maximum amount of load that can be shed in that area. The load shedding flexibilities of different areas in the building are the inputs to a load shedding distribution algorithm. In Section IV, we describe the generic operation of a lighting system according to our model, and describe two load shedding distribution algorithms. In Section V, we consider a distributed implementation of one of these load shedding distribution algorithms. In Section VI, we compare one of our methods with the simple method of uniform load shedding. We end with conclusions in Section VII.

II. CURRENT METHODS FOR LIGHTING CONTROL SYSTEMS FOR DEMAND RESPONSE

Lighting control systems have been described in literature wherein luminaires are uniformly and simultaneously dimmed using load-shedding ballasts and the trigger to dim is sent using a simple powerline broadcasting mechanism [7]. This simple mechanism implemented in load-shedding ballasts enables the lighting system to provide cost-effective electrical demand response. In [8], an alternate method for automatically reducing power consumption of a lighting system using a pre-configured multi-tiered system and preset thresholds is

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described. The above methods have some disadvantages, as discussed next.

A building facility usually is sub-divided into different areas, e.g. corridor, workplace, reception, that serve different purposes. Each functional area may have different illumination requirements. Also, they may have different *flexibilities* towards load shedding. For instance, some areas may tolerate an illumination level reduction up to 50% while others may only tolerate a reduction up to 20%. Load shedding by uniformly dimming all the luminaires, as described in [7], does not take into account this flexibility: it misses out the greater flexibility offered by loads serving some areas, while over utilizing the flexibility of others. The latter situation can adversely affect user comfort and lead to user dissatisfaction. The method in [8] uses manual configuration to specify specific dimming levels for each functional area under a multi-tier load shedding mechanism. This mechanism is cumbersome as it requires for every tier a separate specification of dimming level for all functional areas. Furthermore, the load shedding is still not optimal, since it may shed more than required, as the dimming levels are already predetermined, compromising user comfort unnecessarily.

III. SYSTEM AND METHOD DESCRIPTION

We consider lighting systems as groups of controllable loads. A lighting system comprises luminaires, lighting controller(s) to control the power consumption of individual luminaires, sensors (e.g. occupancy sensor, daylight sensor) that provide information to adjust the dimming levels of luminaires to provide the required service level (e.g., in terms of illumination levels), and communication means for information exchange between the controllers and the sensors. A power sensing unit (e.g., located at the utility meter) measures the power consumption of the entire system. For two of our methods, the system also comprises a central controller, which can be a personal computer, that controls the lighting systems. Such a system with a central controller is illustrated in Figure 1.

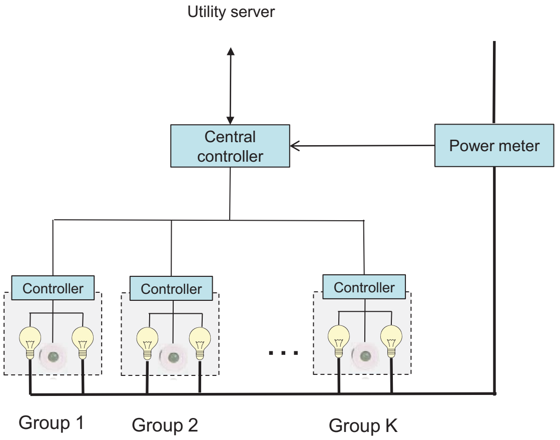

Fig. 1. Overview of lighting system groups

Controllable luminaires are divided into groups based on service requirements of each group. For instance, luminaires within each office room may be grouped together. Each group has a controller that controls the illumination as well as the load control mechanisms described below. For each group a minimum illumination requirement is configured/specified by the user (e.g. facility manager), depending on the end-use of the service area. We denote the minimum illumination requirement of group k at instance t as $I_{min,k,t}$. The power consumption $P_{min,k,t}$ to satisfy the minimum illumination requirements can be calculated by the group controller for group k. Note that the group controller will take into account the daylight and user occupancy in adjusting the dimming level of the luminaires. When there is a change in daylight condition, the group controller will re-calculate $P_{min,k,t}$ based on $I_{min,k,t}$.

In the remainder of the paper, we will describe the action of the system in case of a *load shedding event* under a demand response request, when the system is required to reduce its power consumption by an amount ΔP_t. Various triggers can initiate a load shedding event. One trigger is the reception of a new (lower) system target power consumption at the interface to the smart grid. The required power reduction ΔP_t then equals the difference between the current power consumption, as read from the power meter, and the system target power consumption. Another trigger is that the current system power consumption, as read from the power meter, exceeds the current system target power consumption because of changed system conditions, e.g. because more areas have become occupied. Yet another trigger is that power consumption has recently been high and needs to be reduced in order to stay within a given energy budget over some time interval.

It is the aim of the paper to describe methods for distributing the load shedding amount ΔP_t over the various groups. For this description, we introduce *load shedding flexibility* $LSF_{k,t}$ of group k at instance t defined as

$$LSF_{k,t} = P_{k,t} - P_{min,k,t}, \tag{1}$$

where $P_{k,t}$ is the power consumption of group k at instance t. The load shedding flexibility $LSF_{k,t}$ thus equals the maximum amount of power that can be shed in group k while satisfying the minimum illumination requirements for group k at instance t.

We note that a lighting system may comprise loads that are not automatically controllable. Such loads may be modeled as loads having a load shedding flexibility equal to zero, or, more simply, they can be ignored if all decisions are based on a target system power *reduction*.

Finally, we remark that the load flexibilities can be used to initiate a load shedding event. Indeed, if the price of electricity is high, the facility manager may request the current load flexibilities and sum them up. This sum equals the amount of load that can instantaneously be shed while satisfying all minimum illumination requirements. Based on this sum and the current price of electricity, the facility manager may decide to initiate a load shedding event.

IV. SYSTEM WITH A CENTRAL CONTROLLER

In this section, we assume that the lighting system has a central controller, e.g. a personal computer. We denote the number of groups in the system by K. We describe below how the system reacts in case of a load shedding event where the amount of power to be shed equals ΔP_t.

1) The central controller requests all group controllers to send their load shedding flexibilities.
2) Each group controller sends its load shedding flexibility to the central controller.
3) After reception of all load shedding flexibilities, the central controller checks if $\sum_{k=1}^{K} LSF_{k,t} < \Delta P_t$. If so, the requested target power reduction cannot be met without violating at least one minimum illumination requirement and special action must be taken. Otherwise, based on ΔP_t and the load shedding flexibilities, the central controller runs a load shedding distribution algorithm and determines for each group k a load shedding amount $\Delta P_{k,t}$ such that $\Delta P_{k,t} \leq LSF_{k,t}$ and $\sum_{k=1}^{K} \Delta P_{k,t} \geq \Delta P_t$.
4) The central controller sends to each group controller k information enabling it to compute $\Delta P_{k,t}$.
5) Using the information sent by the central controller in the previous step, each group controller k determines its target power shedding value $\Delta P_{k,t}$, calculates the target power consumption for group k as $P_{tgt,k,t} = P_{k,t} - \Delta P_{k,t}$, and computes the corresponding dimming levels for all the luminaires within the group and adapt them accordingly.

We now discuss two load shedding distribution methods that can be used in step 3.

A. LSF-proportional load shedding

With the load shedding distribution method in this sub section, the amount of power shed in group k is proportional to $LSF_{k,t}$. As a result, if the power consumption of a group k is close to its minimum $P_{min,k,t}$, then its reduction in power consumption will be very small. The method is simple, and allows the central controller to send one single value (in broadcast) that allows each group controller k to compute its load shedding amount $\Delta P_{k,t}$.

The method works as follows. In step 4 above, the central controller broadcasts the value z_t defined as

$$z_t = \frac{\Delta P_t}{\sum_{k=1}^{K} LSF_{k,t}}.$$

In step 5, upon reception of z_t, group controller k calculates its target power shedding value $\Delta P_{k,t}$ as $\Delta P_{k,t} = z_t LSF_{k,t}$.

Note that the definition of $\Delta P_{k,t}$ implies that

$$\Delta P_{k,t} = \frac{LSF_{k,t}}{\sum_{k=1}^{K} LSF_{k,t}} \cdot \Delta P_t. \tag{2}$$

From Equation 2 it readily follows that $\sum_{k=1}^{K} \Delta P_{k,t} = \Delta P_t$, that is, the amount of power jointly shed by all groups equals the amount of power that is to be shed in the system to meet the target power consumption.

B. Load shedding equalizing relative illumination changes

The load shedding distribution method from Section IV-A is based on parameters values in the electrical domain; it does not explicitly take into account the effects of the load shedding that are of relevance to the end user, *viz* the effects on the illumination conditions. In this subsection, we describe a more involved load shedding distribution method that aims to optimize an objective function of parameters related to illumination taking into account constraints on parameters in the electrical domain. It also takes into account that equal power consumption changes with different luminaires may result in different illumination changes.

We denote the difference between the illumination level in group k before and after load shedding as $\Delta I_{k,t}$. As we perform a load shedding, the illumination level in a group decreases, so $\Delta I_{k,t} \geq 0$. We now write

$$\Delta I_{k,t} = \beta_k \Delta P_{k,t}.$$

That is to say, the change of illumination level $\Delta I_{k,t}$ is proportional to the change of power consumption $\Delta P_{k,t}$ with a coefficient β_k. A larger β_k indicates a more efficient light source, i.e., a large variation of illumination level only needs a small variation of power.

Here we made two assumptions: 1) for each light source, the change of illumination level is linearly related to the change of power consumption level, and 2) each group contains one type of light source. The first assumption is widely recognized for various types of dimmable light sources [9, p. 93]. The second assumption can be satisfied by proper grouping of the light sources.

We wish that a load shedding action results in a minimal user discomfort. The absolute change of illumination level, however, may not reflect the perceived discomfort by the user. For example, considering $\delta_{I,k} = 50$ lux, changing from 1000 lux to 950 lux may not be noticeable, while changing from 100 lux to 50 lux may be very disturbing. This intuitive notion is supported by the relative visual performance model [10, Sec. 4.3.5] that predicts the effect of lighting conditions on visual performance. In particular, it states the relevance on human task performance of the luminance contrast C defined as $C = (L_t - L_b)/L_b$, where L_b is the luminance of the background and L_t is the luminance of the detail. Inspired by this model, we propose as measure of user discomfort not the absolute change in illumination level, but the change in illumination level normalized to the current illumination level,

$$x_k = \Delta I_{k,t}/I_{k,t} = (\beta_k/I_{k,t})\Delta P_{k,t}. \tag{3}$$

As a fairness criterion, we strive to make the relative illumination changes of the groups as equal as possible. This has the additional advantage that contrast changes in visually adjacent areas, e.g. between an office room and the hallway next to it, are small. We quantify“as equal as possible” as follows: given a vector $\mathbf{x} = [x_1\ x_2\ \cdots x_K]^T$, we measure the difference among its entries x_k using the cost function J defined as

$$J = \sum_{k=1}^{K}(x_k - \bar{x})^2, \text{where } \bar{x} = 1/K \sum_{k=1}^{K} x_k$$

We can find the best values for $\Delta P_{k,t}$ by formulating and solving a constrained optimization problem as in Table I. A numerical example is given in Table II.

TABLE I
OPTIMIZED LOAD SHEDDING DISTRIBUTION

Input: ΔP_t, $LSF_{k,t}$, $\beta_k/I_{k,t}$.
Output: $\Delta P_{k,t}$.
Solve the constrained optimization problem:

$$\hat{\boldsymbol{\delta}} = \arg\min_{\boldsymbol{\delta}} \|(I_K - K^{-1}\mathbf{A}_1)\mathbf{D}\boldsymbol{\delta}\|^2, \tag{4}$$

$$\text{such that } \mathbf{1}^T\boldsymbol{\delta} \geq \Delta P_t, \text{and } 0 \leq \delta_k \leq LSF_{k,t},$$

where I_K the $K \times K$ identity matrix, $\mathbf{A}_1$ is the $K \times K$ all-one matrix, $\boldsymbol{\delta} = [\delta_1\ \delta_2\ \cdots\ \delta_K]^T$ is a $K \times 1$ vector, and $\mathbf{D}$ is the $K \times K$ diagonal matrix with the k-th diagonal element being $\mathbf{D}_{k,k} = \beta_k/I_{k,t}$. The solution to (4) can be obtained by well-developed quadratic programming (QP) algorithms, e.g., the active-set method [11]. The k-th entry of $\hat{\boldsymbol{\delta}}$ equals the power change $\Delta P_{k,t}$ in group k.

TABLE II
AN EXAMPLE (WITH ΔP_t = 60 W)

Group index k	1	2	3	4
QP Input:				
P_k, (W)	62	136	104	108
$P_k^{\min}$, (W)	50	100	92	60
β_k, (lux/W)	5	10	8	3
I_k, (lux)	250	1300	700	300
QP output:				
$\Delta P_{k,t}$, (W)	8.3	22.6	12	17.1
x_k	16.7%	17.4%	13.7%	17.1%

The optimized power consumption change $\Delta P_{k,t}$ results in a normalized illumination level change x_k as equal as possible among the 4 groups, meanwhile satisfying all the power constraints of different groups. As shown in Table II, groups 1, 2 and 4 reduce their illumination level by approximately 17% each, while group 3 reduces its illumination level by 13.7% and just reaches its $P_k^{\min}$ of 92 W.

V. DISTRIBUTED IMPLEMENTATION OF LSF-PROPORTIONAL LOAD SHEDDING

In this section, we describe a distributed implementation of one of the load shedding distribution algorihms, - the LSF-proportional method of Section IV-A. In this distributed implementation, each group controller determines the required dimming levels under the absence of any central controller. A group controller can only communicate with neighboring group controllers (via wireless or wired links).

To determine dimming levels, group controller k needs to compute at instance t its target power shedding value (cf. Equation 2)

$$\Delta P_{k,t} = \frac{LSF_{k,t}}{\sum_{k=1}^{K} LSF_{k,t}} \cdot \Delta P_t. \tag{5}$$

The value ΔP_t may be computed at the utility meter and conveyed to the group controllers. The quantity $LSF_{k,t}$ is locally known at the controller. The quantity $\sum_{k=1}^{K} LSF_{k,t}$ however needs to be computed in a distributed manner. Equivalently, the average load shedding flexibility $\frac{1}{K}\sum_{k=1}^{K} LSF_{k,t}$ needs to be computed in a distributed manner, given that the total number of controllers K is known. Efficient distributed protocols for computing averages are known in literature (see e.g. [12]). In particular, in iteration n, group controller k computes an estimate $lsf_k(n)$ of the average load shedding flexibilities as

$$lsf_k(n) = w_{kk}(n)lsf_k(n) + \sum_{m\in\mathcal{N}_k} w_{km}(n)lsf_m(n), \tag{6}$$

where $w_{km}(n)$is a weight at iteration n and $\mathcal{N}_k$ is the set of controllers that group controller k can communicate with. The value $lsf_k(n)$ is communicated to neighboring group controllers in iteration n. The value $lsf_k(n)$ converges to the average $\frac{1}{K}\sum_{k=1}^{K} LSF_{k,t}$ for sufficiently large values of iterations n. The weights w_{km} may be chosen in a variety of ways (see e.g. [12]).

VI. NUMERICAL RESULTS

In this section, we compare LSF-proportional load shedding (of section IV-A) and uniform load shedding. For notational convenience, as compared to previous sections, we suppressed the time index t. The methods are compared for load shedding with dimming level d, with $0 < d < 1$. With dimming level d, the current system power consumption P_{sys} is reduced to $(1-d)P_{sys}$. In subsection VI-A, we present the analysis of the methods. In subsection VI-B we present numerical results for an exemplary office floor.

A. Analysis

We denote by $P_k^u(d)$ and $P_k^{LSF}(d)$ the power consumption in group k after dimming with level d if uniform shedding resp. LSF-proportional shedding is used for the load shedding distribution across groups. The current power consumption in group k is denoted by P_k, and its minimum power consumption for respecting the minimum illumination requirements by $P_{min,k}$.

By the definition of uniform dimming, we have for each group k that

$$P_k^u(d) = (1-d)P_k.$$

We denote by d_{th} the dimming level for which the target power reduction equals the sum of all load shedding flexibilities, *i.e.*

$$d_{th} \cdot P_{sys} = \sum_{k=1}^{K} LSF_k.$$

For $d < d_{th}$, LSF-proportional load shedding operates as described in Section IV-A. For $d > d_{th}$, dimming with level d cannot be done without violating the minimum illumination for at least one group. We extend LSF-proportional shedding as follows: first, all groups reduce their power consumption to their minimum level. The remaining amount of load to be shed is distributed uniformly over all groups. As a result, we have

$$P_k^{LSF}(d) = \begin{cases} P_k + (P_{k,min} - P_k)\frac{d}{d_{th}} & \text{for } 0 < d < d_{th} \\ P_{k,min} \cdot \frac{1-d}{1-d_{th}} & \text{for } d_{th} < d < 1 \end{cases}$$

B. *Numerical results for an exemplary office floor*

In this section, we numerically work out the results of the previous section for an exemplary office floor. We assume that there are twelve office rooms, each with an area of 18–20 m^2 and installed lighting power of 200 W, roughly corresponding to 11 W/m^2 as in [13]. We use the settings of Table III. For simplicity, we assume there are three different values for P_k and $P_{k,min}$. The values of P and P_{min} for the different rooms are due to personalized power settings, different amounts of incoming daylight and different tasks to be performed in different rooms. The current system power consumption P_{sys} thus equals 2300 W. The sum of the minimum powers equals 1780 W, so the threshold dimming level d_{th} equals $1-(1780/2300) \approx 0.226$. In Figure 2 we represent the power usage as a function of the dimming level d for each of the office room types A, B and C; the curves labeled with "uni" and "lsf" refer to uniform dimming and LSF-proportional load shedding, respectively. In order to allow for easy comparison of different groups, we plot on the y-axis for group k the value of $p_k(d)/P_{k,min}$. Hence, for each group k, the minimum illumination requirement is met as long as the curve for group k is above the line $y = 1$.

TABLE III
NUMERICAL VALUES FOR EXEMPLARY OFFICE FLOOR

	$P[W]$	P_{min} [W]	# rooms
Office room type A	200	170	7
Office room type B	180	130	3
Office room type C	180	100	2

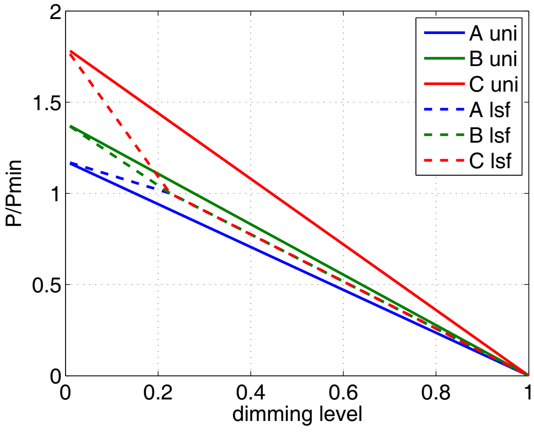

Fig. 2. Power usage with dimming level d

We see that with LSF-proportional load shedding, all groups respect their minimum illumination requirements as long as $d < d_{th}$, while with uniform dimming, groups A, B and C start to violate the minimum illumination requirements for $d = 30/200 = 0.15$, $d = 50/180 = 0.278$ and $d = 80/180 = 0.444$, respectively. Stated differently, with LSF-proportional load shedding, all rooms satisfy their minimum illumination requirements if $d < d_{th} \approx 0.226$, while no room satisfies its minimum illumination requirements for $d > d_{th}$. With proportional dimming, the number of rooms satisfying their minimum illumination requirements equals 12 if $d < 0.15$, 5 if $0.15 < d < 0.278$, 2 if $0.278 < d < 0.444$, and 0 if $d > 0.444$.

VII. CONCLUSIONS AND REMARKS

We presented load control methods in lighting systems towards offering demand response services on smart grids. Different methods were presented for distributing load shedding across groups of lighting systems based on the load shedding flexibilities of the respective groups. This allows to simultaneously meet the minimum illumination requirements for all groups for a larger load shedding amount than with uniform load shedding.

In future work, we will consider a more general case by associating to each group k a utility function of $P_{k,t}$ and maximize the total utility function under different utility models [14]. Amongst others, it would allow to consider the case in which some lights can be dimmed with very little discomfort compared to other lights (e.g. decorative light versus task lights).

Similar to load reduction, strategies for load restoration may be considered and will be part of future work. We will also consider practical challenges in implementing the proposed load reduction strategies.

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VIII. BIOGRAPHY

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