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An Energy Efficient Dc Lighting Grid Using IOT

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ABSTRACT: *This paper highlights the benefits and possible drawbacks of a DC-based lighting infrastructure for powering Light Emitting Diode (LED)-lamps. It also evaluates the efforts needed for integrating the so called smart lighting and other sensor/actuator based control systems, and compares existing and emerging solutions. It reviews and discusses published work in this field with special focus on the intelligent DC-based infrastructure named EDISON that is primarily dedicated to lighting, but is applicable to building automation in general. The EDISON "PowerLAN" consists of a DC-based infrastructure that offers telecommunication abilities and can be applied to lighting retrofitting scenarios for buildings. Its infrastructure allows simple and efficient powering of DC-oriented devices like LED lamps, sensors and microcontrollers, while offering a wired communication channel. This paper motivates the design choices for organizing DC lighting grids and their associated communication possibilities. It also shows how the EDISON based smart lighting solution is evolving today to include new communication technologies and to further integrate other parts of building management solutions through the OneM2M (Machine to Machine) service bus.*

Keywords: *DC-grid; lighting control; LED drivers; power line communication; OneM2M; IoT; wireless sensor networks; lighting; building automation; REST ful.*

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I. Introduction

In the mission to reduce greenhouse gas emissions, the European Union enacted the "2030 climate and energy package" in October 2014, continuing on the "2020 climate and energy package" [1]. The package sets three key targets: cut 40% of greenhouse gas emissions (from 1990 levels), generate at least 27% of energy from renewables and improve the energy efficiency by at least 27% (compared to the projected energy usage). Over the past years, a substantial effort has been put in optimizing the generation and consumption of energy within the European union. The most recent report from 2017 using statistical data from 2015 indicates a reduction of 22.1% greenhouse gas emissions compared to 1990 levels, a 16.7% renewable energy share of gross final energy consumption and a 15.9% energy reduction compared to the hypothetical projection [2]. Although being on track, additional efforts will have to be made to achieve the aforementioned 2020 and 2030 energy targets.

The U.S. Energy Information Administration estimates that in 2016 approximately 279 billion kWh of electricity was used for lighting by the residential and commercial sectors in the United States of America, corresponding to approximately 10% of the total energy consumption of these sectors and 7% of the total electrical consumption in the USA [3]. Concrete data about these proportions within the European Union is not readily available; however, it is reasonable to expect similar ratios. Migrating to LED (Light Emitting Diode) lighting allows considerable energy savings due to its superior efficacy compared to halogen and fluorescent lighting; further improvements are soon expected. The initial cost of purchasing LED lighting has plummeted in recent years, often making it the most economical choice. For those reasons, LED lighting is becoming omnipresent [4]. Light Emitting Diodes and digital electronics in general operate on DC and require convertors when powered by the AC mains [5]. Therefore, the idea has arisen to feed the lighting infrastructure with a low-voltage DC system instead of the mains. This centralized AC to DC conversion approach allows far simpler and more efficient powering of LED lamps, as it avoids an AC to DC converter in every lamp. Simultaneously, this DC system facilitates the integration of digital electronics, simplifying smart lighting control, which improves user comfort and satisfaction and allows for obtaining further energy savings. Additionally, the distribution by means of low-voltage DC reduces the shock hazards that can be induced by the lighting infrastructure.

In this paper, we briefly explain how LED technology has revolutionized the lighting industry. We introduce the basic functioning of LEDs to clearly explain the different ways for powering them. After pinpointing the possible advantages of using a DC grid for feeding the LED lamps, the additional reasons for going back to DC-based electricity distribution are summarized. Benefits and drawbacks of DC-based lighting are further explored. Important factors are ease of maintenance, safety and energy efficiency. For the latter, some measurements are included to give a coarse idea of the energy wasted in the conversion and driver circuitry for AC- and DC-based grids. To achieve a substantial energy saving while keeping or augmenting the user's comfort, the concept of smart lighting is introduced. The paper discusses the different solutions for integrating an intelligent control system in the lighting infrastructure to be able to automatically dim or switch on or off the lamps based on user presence (or user's preferences) and on the availability of daylight scavenging. While presenting the flexibility of DC-based lighting solutions, the paper clearly motivates the design choices taken for the EDISON project [6–8] and introduces the main building blocks of the EDISON smart lighting system. It also introduces the latest efforts to make the EDISON smart lighting solutions interoperate with other (building management) systems.

II. Powering LEDS

To clarify what a LED needs to produce a stable and controllable amount of light, we briefly illustrate LED powering fundamentals. In most cases, LEDs are fed through the traditional AC-based lighting grids connected to the mains (230 V or 110 V AC). We will have a look at the electronic circuits needed between the grid and the LEDs, typically referred to as LED drivers. For convenience, LED lamps as a whole are often a combination of the actual LEDs and a LED driver. This typical setup is looked at more closely.

Direct current has recently been making a comeback as a potent alternative means for distributing electrical energy and can be beneficial for creating a DC-based lighting grid for LED lamps. To understand the challenges, a comparison is made between the electricity distribution aspects of AC and DC grids. Subsequently, a low-voltage DC lighting infrastructure with DC-based LED drivers is discussed. To highlight some important issues, the energy efficiency of some representative AC- and DC-based LED lighting solutions is evaluated.

2.1. LED Powering Fundamentals

Light Emitting Diodes are a special subset of diodes producing photons when current flows through them. There is a quasi-linear relationship between the current going through a LED, and the brightness of the LED. Indeed, increasing the current results in more electrons and holes recombining and thus more photons being generated. This relationship can be observed in Figure 2a. Because of the almost linear relationship, it is easy to control the light output of a LED lamp by regulating its current. This is particularly interesting for dimming purposes.

The current does not scale linearly with the voltage though, as is the case with all semiconductor devices. In fact, below a certain voltage, almost no current will flow. Above this threshold, a small voltage increment can potentially result in a large current increment. The current–voltage characteristic of a XM-L LED (Cree, Inc., Durham, NC, USA) is depicted in Figure 2b. Furthermore, this nonlinear current–voltage relationship varies with component spread and is temperature dependent. An increase in temperature increases the current for the same voltage, possibly triggering thermal runaway ultimately leading to the destruction of the oversaturated LEDs. Powering LEDs without any current limiting circuitry is therefore strongly discouraged. Series resistors can be added to the circuit to limit the drift of the operating point. Note that such resistors waste energy, resulting in lower efficiency.

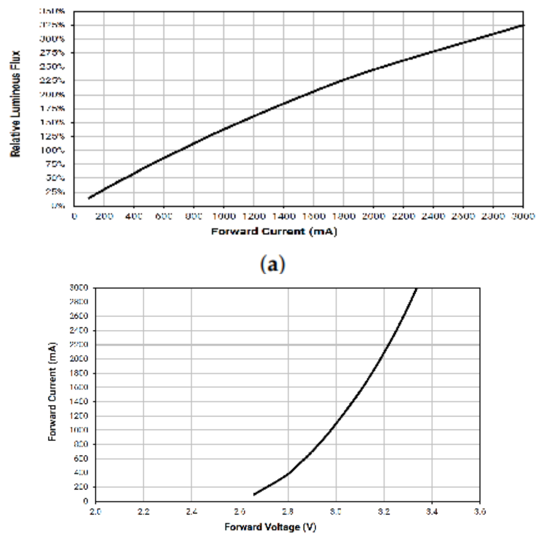

Figure 1. Operating point of a Cree XM-L white LED

Used with permission of Cree, Inc. (a) almost linear relationship between LED current and luminous flux; (b) current–voltage characteristic. Note the non-zero starting x-axis.

2.2. LED Drivers for the Traditional

AC-Grid LED lamps typically consist of two components: the actual light emitting diodes and some power electronics. We highlighted in Section 3.1 why it is recommended to power LEDs by current control, not by voltage control. LED drivers are designed specifically for this purpose. Typically, those drivers are integrated in the LED lamps, although they can also be found as external components. A built-in driver has advantages since the driver is designed specifically for that LED lamp and allows easy installation; a LED bulb can just take the place of a traditional bulb. However, having these electronics integrated often deteriorates the LED lamps' lifetime as they tend to be the weakest point in the chain. Figure 3 shows a typical but simplified design of an AC LED lamp with integrated LED driver.

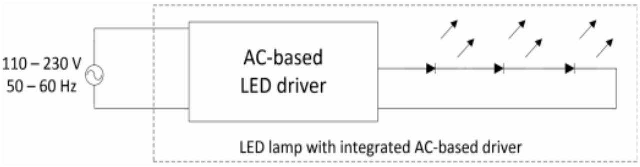

Figure 2. Schematic representation of LED lamp with integrated driver operating on AC.

The goal of an AC-powered LED driver is to produce a stable constant current output from the 50 Hz or 60 Hz AC mains power input. This can be achieved in multiple ways. Several LED driver designs are available, varying in reliability, efficiency, complexity, size, stability and cost. There can also be vast differences regarding dimming support. Dimming will be further clarified in Section 4.2, which treats the control aspect of LED lights.

Some driver designs are very simple and use only passive components. Whereas this is still acceptable for small electrical loads below 25 W, power factor and electromagnetic compatibility (EMC) regulations [16] require complex approaches for more demanding loads. Switched-mode power supplies (SMPS) with power factor correction (PFC) allow high efficiencies while complying to these regulations. These types of converters exist as single-stage, double-stage and even triple-stage designs, and can be galvanically isolated from the mains or directly coupled. Boost-buck is a typical design, depicted in Figure 4 in which the boost stage operates as a PFC, and the buck stage converts down and regulates the LED current. Given the vast amount of possible AC LED driver designs available, it is recommended to consult references [17,18] for an in-depth overview. In [17], a comparison is made between a range of commercial LED driver typologies. Extensive information regarding the design and development of SMPS-based LED drivers is found in [18]. In [19], several SMPS designs are compared and a low cost, high density LED driver is designed. Results on power quality tests are reported in [20].

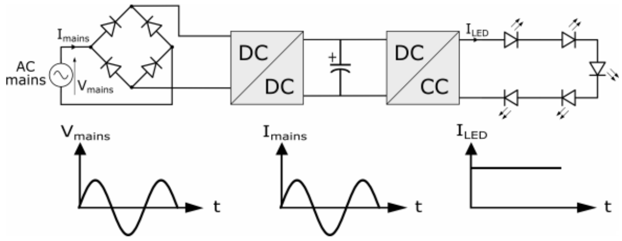

Figure 3. A boost-buck AC LED driver. The bridge rectifier and first DC/DC converter act as a boost stage, functioning as a power factor corrector (PFC). The second stage functions as a constant current source for the LEDs.

The LED driver design specifies the features and compatibility of the entire LED lamp. A LED driver designed to operate on a 230 V 50 Hz mains might not work on a 110 V 60 Hz mains and vice versa, while other designs operate flawlessly within a wide voltage range. In low-cost designs, the output circuit is typically not galvanically isolated from the mains. In this case, extra caution should be taken to properly isolate all metal contacts. Touching these contacts, connected directly to mains, may result in a lethal electrical shock hazards. This potentially dangerous flaw may not only be present in cheap, poorly designed lamps [21]. Issues have also occurred with lamps from renowned brands like Philips. They had to recall 99,000 lamps due to a manufacturing fault possibly leading to a shock risk [22].

2.3. Migrating to DC-Based Distribution

The compatibility of AC-powered LED lamps with the existing infrastructure is convenient but comes at a price. The lamps' safety can be compromised by reckless designs and manufacturing defects, possibly even leading to lethal shocks. Lower efficiencies are noticeable as compared to directly powering with DC. The extra components needed for the AC conversion result in additional points of failure, possibly reducing the lifetime. Additionally bad power factors and electromagnetic interference can pollute the mains.

Given LEDs' DC nature, these issues can be avoided or at least be reduced by migrating to a DC-based lighting infrastructure. Converting the existing lighting infrastructure to DC can appear radical and complex at first sight. In many buildings in Europe, the electric circuitry for lighting and appliances are strictly separated. When this is the case, retrofitting the lighting circuit to DC-based distribution is quite easily achieved. Obviously, the same result is achieved when deploying a completely new electrical infrastructure dedicated to lighting.

III. Controlling Led Lighting

In this section, we will review ways to control LED lighting, generally applicable or specifically for an AC or DC solution. We begin with basic interaction, which is the manual control of the LED lights to their on and off states using switches. Subsequently, we have a look at the dimming capabilities of both the AC and the DC solution.

Automation is playing an increasingly prominent role in the quest to optimize systems. Smart lighting allows more punctual control of the lighting infrastructure resulting in further energy savings and increased user satisfaction. The basic building blocks of smart lighting solutions are introduced and their applicability for DC will be discussed. A dedicated Section 5 will further elaborate on the myriad of choices for organizing communication.

3.1. Basic On/Off Lighting Interaction

Manually controlling the lights by means of interrupting the current flow is the most basic form of interacting with them. This method is self-explanatory and should not need and further explanation—or does it?

Turning off the lights in a DC-based lighting system might appear trivial, but, unfortunately, it is not. An arc occurs when disrupting a sufficiently large current. This phenomenon happens both in AC and DC environments. In AC environments, there are zero-crossings occurring twice per period in which no current flows, which can stop the arc. This is not the case in DC environments, so arcing will not be automatically interrupted. Switching devices, whether lighting switches or relays, need to be specifically dimensioned to cope with the given DC voltages and currents; otherwise, arcing might be sustained and excessive wear will occur in the switching contacts. Looking at the specifications of switches and relays, the maximum switching DC voltages are far lower than their AC counterparts.

When overhauling the lighting infrastructure to DC, it is the perfect moment to upgrade from the classical lighting switches to their electronic variant. After all, this DC infrastructure suits electronics. Transistors are semiconductor devices just like LEDs and are ideal for electronically controlling DC currents. Power metal-oxide-semiconductor field-effect transistors (MOSFETs) with low resistance are a suitable electronical replacement for lighting switches. Although the gate is typically being electronically controlled, it is still possible to do this manually with mechanical switches like lighting switches. Interrupting the signal to the gate is easy, as the gate hardly draws any current. An example circuit involving an N-channel metal-oxide-semiconductor (NMOS) is given in Figure 7. The flyback diode in parallel with the LED drivers protects the MOSFET from voltage spikes caused when interrupting inductive loads.

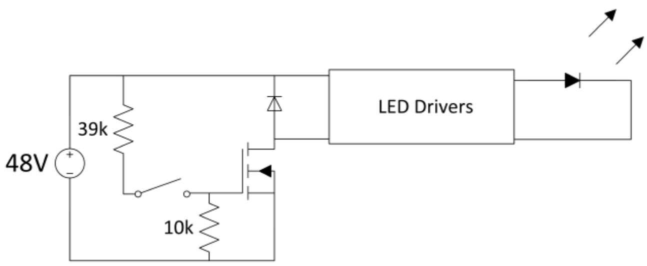

Figure 3. Controlling the DC current flow with a metal-oxide-semiconductor field-effect transistor.

3.2. Dimming

Having the possibility to precisely control the lighting output is an interesting feature. Dimming is frequently used to create different ambiances depending on the mindset and activity. It can also realise significant energy savings. Given the almost linear equation between luminous flux and current flowing through a LED, as mentioned in Section 3.1, LED lighting can potentially lend itself perfectly to dimming control. It is the task of the LED driver to regulate the current flow through the LEDs, hence, when supported, dimming is realized by altering the operating point of the LED driver.

Traditional dimming in an AC lighting infrastructure is realized by cutting off part of the AC voltage waveform, lowering the average voltage and power. This works well for resistive loads like incandescent lamps but is harder to achieve for LED lighting, as typical LED driver designs try to keep the output current going to the LEDs constant [38]. Some types of LED drivers have additional electronics for detecting those voltage waveform manipulations and can be dimmed by conventional AC dimmers. Others allow dimming by having separate dimming control pins. The very basic LED drivers are fixed and will not dim at all, start flickering or might even be damaged when being controlled by AC-based light conventional dimmers.

External LED drivers, both AC- and DC-powered, can be equipped with dimming control pins featuring one or multiple control methods. These methods can be diverse and depend on the LED driver in question. Typical methods are controlled through changing the resistance value of a potentiometer, controlled through a 0–10 V signal, and controlled through a pulse-width modulated (PWM) signal. More complex LED drivers can also support digital addressable lighting interface (DALI) or similar networking technologies for remotely controlling the lighting.

PWM is the de-facto standard when it comes to simple and robust digital modulation techniques. By only providing current to the LEDs during the active part of the PWM duty cycle, it is possible to dim a LED lamp. The Mean Well LDD-H series are cost-effective external DC-powered LED drivers that allow PWM dimming control [39]. Do note that some considerations must be taken into account when selecting the PWM actuation frequency. Below approximately 100 Hz flickering might be detected by the human eyes. Now that it is possible to precisely control the LED lighting infrastructure, it is a good idea to automate this system.

IV. Conclusion

This paper guides the reader through the design choices for deploying DC or AC infrastructure destined for LED based lighting. It highlights basic concepts, reviews the most helpful and important sources of information and applies the obtained insights to qualitatively evaluate a DC- versus AC-powered solution. In the comparison, elements such as safety, regulatory aspects, reliability, complexity, ease of deployment and maintenance are taken into account. It is also strongly based on our own experience gained from building and exploiting several DC pilots on the VUB campus and in other sites in Europe. The comparison includes a thorough overview on how to organize smart lighting solutions with a strong focus on the communication infrastructure that supports smart lighting. The paper motivates why DC is making a come-back and why it is well fit for organizing power transfer to the lamps. The EDISON solution uses a 48 VDC system, as trade-off between distribution voltage, safety and device support. Measurements conducted on AC- and DC-powered LED drivers, and on 48 VDC power supplies, indicate that a well-designed DC LED lighting solution can achieve superior efficiency over an AC solution. The retrofitting action performed in the VUB campus restaurant demonstrates that the DC-based, ICT (Information and Communications Technology) controlled lighting system operates flawlessly. It shows the energy savings mainly obtained from replacing compact fluorescent bulbs and fluorescent tubes into their DC-powered LED substitutes, and the extra savings obtained by dimming the lights when possible. Respectively, 59% and 67% of the energy is saved compared to the original lighting system. Aside from these energy savings, the new LED lamps provide a 20% increased luminance level.

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