

Editorial

Latest Developments in LED Drivers

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1. Introduction

Although the phenomenon of electroluminescence was discovered by H. J. Round of Marconi Laboratories using a silicon carbide (SiC) crystal in 1907 [1], light-emitting diode (LED) technology was not to become a reality until the beginning of the 1960s [2]. However, the first LED technology emitting visible light was very inefficient until the 1990s. The major milestone in this field of knowledge was the invention of the first blue LED using GaN in 1993 by Shuji Nakamura of the Nichia Corporation [3] in parallel with Isamu Akasaki and Hiroshi Amano at Nagoya University. Their work made possible the reality of a high-efficiency LED emitting white light. This achievement received very special recognition by the Royal Swedish Academy of Sciences in the form of the 2014 Nobel Prize in Physics.

Since then, LEDs emitting white light have been considered the foremost alternative to replace inefficient light sources (e.g., incandescent, halogen, fluorescent, compact fluorescent sources, etc.). Nowadays, due to reductions in manufacturing cost, LEDs are increasingly becoming our main source of artificial light in many applications (e.g., street lighting, automotive, residential lighting, etc.). The reason why LEDs have been so successful in the lighting market lies in their excellent characteristics in comparison to conventional lighting solutions: long lifetime, low maintenance requirements, environment friendliness, luminous efficiency, controllability in both light and color, lack of warm-up period, reliability and high power density.

Given that LEDs are diodes, it is necessary to control their direct current (dc) forward current. The devices fulfilling this task are known as LED drivers. It is essential that these devices do not limit the benefits and performance of LEDs. Therefore, LED drivers must be as efficient, compact and durable as LEDs, comply with very strict regulations, and adequately control the output current. These requirements have made the driving of LED lamps a significant field of research in power electronics, where the main topics of interest are: LED modelling, alternating current–direct current (ac-dc) LED drivers, dc–dc LED drivers, efficient dimming and efficient current equalizing in multi-array LED lamps, as well as new trends in LED lighting such as visible light communication (VLC) and medical applications for healthcare enhancement among others.

2. The Present Issue

This Special Issue features 10 articles highlighting recent breakthroughs in LED modelling, the integration of LED drivers, ac–dc LED drivers, dc–dc LED drivers and VLC systems. A brief introduction to the contents of these papers follows below.

Papers [4] and [5] discuss the modelling of LEDs. It is crucial to predict either the electrical or the lighting behavior of LEDs. The transfer of this prediction into mathematical models could help us assess LEDs in advance and hence implement very accurate control strategies in LED drivers in order to perform very precise, complex tasks. Here the use of digital control becomes especially relevant. A novel algorithm is presented in [4] to construct LED radiation patterns with greater accuracy compared to their conventional counterparts. This algorithm is especially useful for short distances in indoor applications. Experimental verification demonstrates a significant reduction in the

approximation error with respect to reality, obtaining errors close to 1.18%; i.e., two-times lower than traditional algorithms. Another type of LED characterization, although now from the point of view of correlated color temperature (CCT) and illuminance, is proposed in [5]. The paper experimentally characterizes LEDs with the aim of exporting this data into a precise mathematical model. Using this approach, the suitable output current of the LED driver can be estimated so as to obtain the desired CCT and illuminance values. Experimental results report an error of 0.3% for CCT and 1.5% for illuminance in the tunable, novel lighting system installed in the Scrovegni Chapel, Padua, Italy.

Integration is currently a “hot” topic in power electronics, and hence in LED drivers. Integration makes it possible to design LED drivers with fewer components and higher power density because both the overall number of interconnections and the parasitic elements associated with the layout are always reduced. An integrated controller (IC) LED driver is presented in [6]. This is the first case of heterogeneous integration of GaN power devices, both GaN LED and GaN field-effect transistor (FET) (i.e., EPC2036), with a two-stage operational amplifier using CMOS DMOS (BCD) circuits. The prototype of the IC LED driver with an output power of 1.36 W has been experimentally tested, achieving stable thermal performance in a compact size of $2.4 \times 4.4 \text{ mm}^2$. Moreover, the IC LED driver emits visible light at a wavelength of approximately 454 nm, being the very first promising step for biological and life science applications.

Due to the fact that single-phase ac mains is the primary power supply in homes, offices, streets, etc., ac–dc LED drivers are required to ensure good performance and compliance with regulations (i.e., efficiency, rated life-time hours, harmonic injection, dimming performance and flicker free operation). Paper [7] presents a very practical approach to the classic two-stage solution for ac–dc LED drivers using commercial ICs. The first stage is a boost converter (i.e. power factor correction, PFC, converter), dedicated to achieving a high power factor (PF) and low total harmonic distortion (THD). The second stage is an LLC resonant converter with soft-switching operation dedicated to providing galvanic isolation and control of the forward current of LEDs. An experimental prototype is designed, paying special attention to achieving compliance with IEC61000-3-2 and CIRSP 15:2009 standards. The 150 W street lighting prototype achieves a PF of 0.97, a THD of 7% and a maximum efficiency of 91.7%. Following on from ac–dc LED drivers, the next proposals are those that can be considered quasi-single-stage ac–dc LED drivers. They cannot be considered two-stage solutions for ac–dc LED drivers, but they do not fall within single-stage solutions for ac–dc LED drivers. The integration of an interleaved buck-boost PFC converter with an LLC resonant converter with soft-switching operation is presented in [8]. A reduction in the number of components is achieved compared to the two-stage solution by sharing the main transistors of both stages. Furthermore, the integration enables interleaving operation with two input-coupled inductors, thereby reducing the input current ripple. The topology maintains high efficiency by reaching zero voltage switching (ZVS) at the main switches and zero current switching (ZCS) at the output diodes within the entire output power range. The functionality of the 144 W ac–dc LED driver for street lighting applications is validated, displaying a PF >0.97 , an output current ripple $<2\%$ and a maximum efficiency close to 90%. Another type of quasi-single-stage ac–dc LED driver is presented in [9]. In this case, the main concern is the elimination of the most limiting element in terms of lifespan (i.e., the electrolytic capacitor). In this paper, a current-fed bidirectional buck converter is used as a series post-regulator. This converter helps to decouple the ac power from the input and circumvents the use of the traditional electrolytic capacitor at the output of the PFC stage. The proposal has two major advantages: first, optimization of the inductor design, and second, enhancement of the output dynamic response of the ac–dc LED driver. This means that this solution is suitable for controlling the luminous flux by controlling the forward current of LEDs (i.e., it is suitable for dimming).

Sometimes, the two-stage solution for ac–dc LED drivers is unable to ensure proper control of the forward current of each LED in complex LED arrangements (i.e., multi-string LED configurations). In this case, the traditional two-stage solution becomes the three-stage solution for ac–dc LED drivers employing a post-regulator per string. This post-regulator is a dc–dc LED driver that must be efficient

and have fewer components in order to minimize the impact of a new converter connected in cascade. A novel post-regulator based on a single-switch Class-E resonant dc–dc converter is presented in [10] and [11]. First, the steady-state analysis, dynamic analysis and design guidelines of this novel post-regulator are provided in [10]. The main benefits of this post-regulator are: fewer components, high efficiency due to soft-switching operation and a reduction in the traditional high-voltage stress of converters inherent to the Class-E family. Second, a simplified dynamic analysis is presented in [11] aimed at putting forward this post-regulator as a power source. Feedback loop control is optimized in order to reduce low-frequency ripple at the forward current of LEDs while providing dimming control. The 40 W experimental prototype shows not only a very high efficiency at the rated output power, but also an efficiency of over 90% throughout the entire output power range.

The final two papers, [12] and [13], introduce novel solutions to a new trend in LED drivers: VLC. The need for VLC-LED drivers derives from the fact that the RF spectrum is limited and expensive. Therefore, complementary wireless transmission techniques must be adopted to send information. This is the case of VLC-LED drivers, which can perform lighting and communication tasks thanks to the principal benefits of LEDs: their accuracy and fast lighting response. This novel task for LED drivers (i.e., communication) supposes major challenges in the design of dc–dc converters, which act as VLC-LED drivers: very high efficiency, a very fast output response and significant output power levels associated with the emitted light in order to cover real distances. The steady-state and dynamic analysis of the two-phase series-parallel resonant converter is presented in [12]. This topology is used to implement a VLC-LED driver with a pulse-based modulation (PBM) scheme. A 120 W experimental prototype is tested, achieving bit rates of 10 kbps. Finally, [13] presents a set of solutions for VLC-LED drivers based on the adaptation of traditional solutions either to improve efficiency or linearize RF power amplifiers (RFPAs) for VLC. Experimental prototypes demonstrate that the adaptation of the outphasing technique and the linear-assisted technique, using Class-E RFPAs, is found to be very interesting in order to efficiently reproduce more complex modulation schemes (e.g., quadrature amplitude modulation, QAM, and phase-shift keying, PSK). The experimental verification reports high bit rates (i.e., 4 Mbps) and efficiencies close to 90%.

3. Future

From my point of view, we can predict the future of LED drivers by considering three different lines of research. First, considering LED drivers used for classical lighting applications, research needs to focus on achieving higher efficiencies, better approaches to meeting high standards and regulations, higher power densities, lower failure and lower cost, as is the case of any topic in power electronics. Second, there is growing demand from customers for all devices to be smart, configurable and connected to the Internet (i.e., the Internet of Things, IoT). Therefore, LED drivers must meet communications requirements in order to reproduce accurate environments for different applications: indoor, outdoor, architectural, horticulture, farming, cattle raising, disinfection and so on. These requirements imply contributions in LED modeling and accurate control strategies. Third, new trends in LED lighting (i.e., VLC, LED medical applications for healthcare enhancement, etc.) will demand high bandwidth solutions that are both compact and light. In this case, LED drivers will need to overcome major challenges in terms of integration, ultra-fast output response and efficiency.

LEDs have been around and have been in practical use for decades now and will undoubtedly continue to be a source of innovation and important technological development. It is very important, however, for LED drivers to keep up with the improvements that LED technology will foreseeably achieve in the future.

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