Failsafe Smart LED Module with Thermal Management, String Current Balancing and Commutation for Lifetime Extension

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Abstract—A new LED driver architecture is presented for increasing the lifetime and reliability of solid-state lighting modules. The architecture targets indoor/outdoor industrial applications, where the overhead cost of a smart LED driver is outweighed by the added value of improved lifetime and fault tolerance. The system includes two complete sets of white LEDs and associated current-mode drivers. The digitally controlled dc-dc converters communicate with each other to smoothly transfer current from one set of LEDs to another at a regular commutation interval. A low-power pulse-frequency-modulation mode is used to conserve power in the LED set that is off. The redundancy is also exploited to perform precise current balancing and health monitoring of the individual LED strings, while the total light output remains constant at all times. The architecture is demonstrated on a 25 W module with 154 white LEDs, which forms 1/4 of a full luminaire.

I. INTRODUCTION

Solid-state lighting using LEDs provides increased mean-time-before-failure (MTBF) and higher efficacy compared to traditional fluorescent, HID and incandescent lamps [1], [2]. The distributed nature of lighting modules in commercial and industrial environments makes them ideally suited to act as sensor nodes, connected in a mesh network, within smart buildings. The Smart Lighting Modules (SLM) can be equipped with a communication transceiver and a wide variety of sensors to locally detect temperature, power consumption, ambient light, occupancy, noise, motion, humidity and smoke, as shown in Fig. 1. The communication can be implemented through either Power Line Communication (PLC), a wireless mesh architecture such as Zigbee, or a dedicated low-voltage serial bus. The real-time measurements can be used either locally, or remotely to improve the safety, comfort and energy footprint of future smart buildings.

This work targets solid-state lighting for high-reliability indoor/outdoor applications, such as semiconductor manufacturing clean-rooms, industrial laboratories, factories/assembly lines and safety-critical environments, such as power generation plants. In these applications, the lighting systems operate continuously, and hundreds or even thousands of lights must be replaced at regular intervals before their end-of-life in order to avoid disruptions. The high reliability applications targeted by this research are ideal for LED deployment, since the initial investment is easily justified by the added value of increased reliability. Power management redundancy is used to potentially double the system lifetime, while eliminating unexpected lighting outages.

Fig. 1. Smart lighting module as an integral component of the smart building concept.

The chosen dual-stage power management architecture is shown in Fig. 2(a). It includes two sets of ac-dc power-factor correction (PFC) rectifiers and two independent, digitally controlled dc-dc converters. Alternatively, the system can work directly from a DC bus, which is an emerging trend [3], [4]. The two dc-dc controllers regularly communicate using a serial bus. The module is outfitted with twice the regular amount of LEDs, as shown in Fig. 4. Each set of LEDs, labeled Set a and Set b, is arranged using a group of \( n \) parallel strings having \( m \) LEDs each and assigned to one of the dc-dc converters in Fig. 2. Each string has a dedicated current balancing circuit consisting of a low-cost, individually addressable digital-to-analog converter (DAC) and a power MOSFET. The placement of the LEDs was optimized to achieve identical optical characteristics from each LED sets. Current is smoothly transferred from Set a to Set b at a commutation frequency of \( f_c = 1/T_c \). As shown in Section V, if \( f_c \) is sufficiently high, this redundancy can also significantly reduce the LED junction temperature, \( T_j \), which further leads
to improved MTBF [5]. The LED lifetime, known as LM70 in Fig. 3, is based on the time required for the lumens output to degrade by 30%. The LM70 lifetime of the LED used in this work can be extended by approximately 5 months per 1°C reduction in $T_j$, which is a very compelling reason for performing active thermal management. The LED redundancy is exploited to achieve precise string current balancing for improved optical performance. The redundant architecture is designed to maintain operation if any single block fails.

This paper is organized as follows. The Section II introduces the temperature and commutation control scheme of the two-set LED lighting system. Section III presents the new active string current balancing method. Simulation results are reported in Section IV, using a thermal-electrical-optical system model of the system. Finally, experimental results for the prototype are presented in Section V.

![Fig. 3. LED lifetime based on 30% lumen degradation (LM70) versus junction temperature [6].](image)

**II. TEMPERATURE AND COMMUTATION CONTROL**

Unlike single-stage, AC-fed LED drivers [7], [8], the dual-stage topology of Fig. 2 allows both high power-factor and precise current regulation [9]. The dc-dc converters regulate the LED current and are fed by low-cost ac-dc rectifiers. Each dc-dc converter can draw power from one of the two dc inputs, $V_{in1}$ and $V_{in2}$, by means of the selection signals $sel_a$ and $sel_b$. The independent control circuits of each converter are powered from an auxiliary regulator.

Operating in constant-current mode is generally preferred in LED drivers [10], [11] to achieve a constant luminous flux, $\phi_v$. The primary dc-dc converter runs in average current mode control (ACMC) using a digital compensator.
internal digital references, $i_{La^*}$ and $i_{Lb^*}$ for the current regulation loops are either set to be constant, or they can be controlled by a slow temperature compensation loop using temperature sensors mounted beside the central LED{s}. When enabled, the temperature compensation loop gradually reduces the light output when the ambient temperature increases, in order to guarantee a long LED lifetime. Fig. 5 shows the basic waveform when the converter is working in the regular commutation cycles. During the LED commutation process, $i_{La^*}$ and $i_{Lb^*}$ are slowly ramped in opposite directions, such that a constant total current of $i_{L} = i_{La} + i_{Lb}$ is maintained, in order to reduce the optical disturbance.

![Fig. 5. Ideal waveforms for LED power management circuits during regular cycle.](image)

After the commutation process, the dc-dc converters swap roles from the primary to the secondary converter. The LEDs fed by the secondary converter are turned off using the low-side transistors in the LED module, while the LED bus voltage, $V_{bus}$, is regulated to the turn-off voltage $V_{min}$. The secondary converter operates in burst-mode pulse-frequency-modulation (PFM) to maintain a high efficiency until the next commutation event, which is periodically initiated by the primary converter. Maintaining a regulated output voltage while the LEDs are off reduces the current stress in the power stage and output capacitor during the commutation sequence and minimizes the optical flicker.

III. STRING CURRENT BALANCING

It is common to use multiple strings in LED lighting systems in order to limit the bus voltage. One significant challenge in multi-string systems is the need to balance the string currents. This improves optical and thermal uniformity in the presence of manufacturing variations and changes in operating conditions. In particular, the LEDs which have a current and therefore limit the system reliability.

Past works have demonstrated several passive and active current balancing methods [12]–[16]. The simplest, and least accurate passive balancing method is shown in Fig. 6(a), where series resistors are introduced to each string. Low-side current mirror transistors can be added, as shown in Fig. 6(b), however this does not give individual control access to each string. In transformer isolated LED systems, passive components (capacitor or coupled inductor) are cleverly used to balance the string current [14]–[16]. The schemes offer limited scalability and the use of multiple transformers adds to the cost. Alternatively, sub-string current-mode dc-dc converters can be used to precisely regulate the individual string currents [13], as shown in Fig. 6(c), however the cost and complexity is not practical.

![Fig. 6. (a) Resistor based string current limitation. (b) Linear current regulator. (c) Multi-channel current mode dc-dc converter.](image)

The redundant power management architecture used in this work offers a unique opportunity for precise string current balancing, without the need for sensors and amplifiers in each string, as in [17], [18]. The ideal waveforms during a string balancing cycle for the LED Set $a$ are shown in Fig. 7. The balancing is always performed on the secondary set of LEDs, which are off during regular cycles. The objective of the balancing is to individually adjust the low-side transistor’s $V_{gs}$ in each string using the DACs, such that the currents in the string, $i_{s,a(n-1)}$ are equal to $i_{Lt}/n$ at the given LED bus voltage. The usual commutation process runs from $t_1$ to $t_2$, and the current balancing starts from $t_3$:

1) First Balancing Phase: At $t_3$, the controller sets $i_{La^*}$ and $i_{Lb^*}$ to $i_{Lt}/n$ and $i_{Lt}(n-1)/n$ respectively, such that the total optical output of the LED module is kept constant during calibration. The first string is activated through $V_{gs,a1}$. In the mean time, one string on Set $b$ is turned off to maintain constant optical output. The bus voltage $V_{bus,a}$ is monitored and $V_{gs,a1}$ is adjusted using the serial DAC until $V_{bus,a} = V_{bus,a}'$, where $V_{bus,a}'$ is the bus voltage prior to commutation when phase $a$ is on. Each string is then successively calibrated using the same method. The DAC values are updated one-by-one using the serial bus.

2) Bus Voltage Minimization: After all the strings have been calibrated, the DAC which has the highest $V_{gs}$ setting from the first phase is set to give the maximum possible $V_{gs}$ the DAC could provide. The new bus voltage $V_{bus,a}''$ is sensed for the second round of calibration.

3) Second Balancing Phase: In the second balancing phase, all other strings are re-calibrated to the new voltage $V_{bus,a}''$. The second balancing phase therefore minimizes
$V_{bus,a}$ and subsequently, the losses in all strings in order to achieve the highest possible efficiency.

\[
I_D = nI_s(e^{(V_{th}/m)/aV_t}) - 1, \quad (1)
\]

where $a$ is the diode constant and $V_t = kT_j/q$ is the thermal voltage. The constant, $R_{led}$, represents the parasitic series resistance in the LED. Note that the temperature dependency of $I_s$ is not accounted for in this model. The LED efficacy, $E$ (lm/W), drops linearly with $T_j$ [19] and is given by

\[
E = E_o \left[1 + k_e(T_j - T_o)\right], \quad (2)
\]

where $E_o$ is the nominal efficacy at the reference temperature, $T_o$. The value of $k_e = -0.002$, which represents a 20% drop in efficacy over $\Delta T = (T_j - T_o) = 100$ °C, was used based on the measured luminous flux degradation in [6]. The constant $k_h$, representing the percentage of the electrical LED power, $P_{ed}$, that is transferred to heat, $P_{heat}$. The lumped thermal model includes the junction and case temperature of each set, as well as the common heat sink temperature, $T_{sink}$ and the ambient temperature, $T_A$. The LED junction-to-case thermal resistance, $R_{jc}$, was taken from [6] as 15 °C/W, while the remaining constants, $a$, $I_s$, $R_{led}$, $k_h$, $R_{CS}$ and $R_{SA}$ were obtained through curve fitting.

**IV. Modeling and Simulation**

The simplified model used to simulate the redundant lighting system is shown in Fig. 8, which excludes the balancing resistors, as all LEDs are assumed to be matched in the simulation. Each of the two sets is lumped into one LED model, which includes $n=11$ strings, each with $m=7$ LEDs. The subscripts $a$ and $b$ on all the variables refer to the respective LED sets. The photo-electro-thermal model described in [19] is used to account for the interdependency of the junction temperature, $T_j$, the luminous flux, $\phi$, the LED current, $I_D$ and voltage, $V_D$. Despite several simplifying assumptions, this model was shown to match well with experimental data in [19]. The diode I-V characteristic is given by

\[
I_D = nI_s(e^{(V_{th}/m)/aV_t}) - 1, \quad (1)
\]

where $a$ is the diode constant and $V_t = kT_j/q$ is the thermal voltage. The constant, $R_{led}$, represents the parasitic series resistance in the LED. Note that the temperature dependency of $I_s$ is not accounted for in this model. The LED efficacy, $E$ (lm/W), drops linearly with $T_j$ [19] and is given by

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**Fig. 7.** Ideal waveforms for LED power management circuits during a string balancing cycle.

**Fig. 8.** Lumped model of the two-set LED system.
A dynamic simulation result with the LED commutation enabled is shown in Fig. 10(a), after the system has reached thermal steady-state. The difference between the junction temperature and the case temperature, $\Delta T = T_j - T_{\text{case}}$, grows rapidly once the set is turned on, due to the low internal thermal capacitance, $C_j$, while $T_{\text{case}}$ changes more gradually, since there is a large heat slug soldered to the PCB and hence $C_c > C_j$ in the lumped model.

Finally, the simulation shown in Fig. 10(b) illustrates the advantage of rapid commutation, as the peak value of $T_j$ is reduced as the commutation time is reduced from $T_c = 100$ s to 4 s, due primarily to the thermal capacitance in the surrounding area of the LED.

V. EXPERIMENTAL RESULTS

The system shown in Fig. 2 was implemented to test the fault-tolerant driver concept, including a customized LED module with 154 white LEDs, as shown in Fig. 3(a). A full luminaire would normally contain four LED PCBs and 616 LEDs. Each LED has a nominal luminous intensity of 8.5 cd at $I_s = 100$ mA [6]. The dc-dc converter parameters are as follows, $L = 33 \ \mu\text{H}, C_{\text{out}} = 100 \ \mu\text{F}, f_s = 200$ kHz, $n = 11$, $m = 7$, $I_{Lt} = 1.1$ A, $V_{\text{bus}} = 22.3$ V (nominal). The measured temperature versus $I_s$ is shown in Fig. 12. The $T_j$ can be calculated from the system model of Fig. 8.

Interestingly, if the commutation time, $T_c$, is chosen sufficiently low compared to the system’s thermal time constants, $T_j$ is significantly reduced since the LEDs are not permitted to reach thermal steady-state. Infrared (IR) thermal plots of the LED module in steady-state with commutation disabled are shown in Fig. 11(a) and (b) for Set $a$ and $b$ turned on, respectively. The IR plot for the extreme case of $T_c = 2$ s is shown in Fig. 11(c), where the reduction in $T_j$ is clearly visible. It is expected that since the LED board will be packaged with a heat-sink in the future product, a considerably
Fig. 11. Measured infrared temperature profile of the center of the LED board with (a) Set a and (b) Set b enabled in steady-state. (c) IR plot (zoomed out) during commutation with $T_c = 2$ s, showing the reduced temperature over the module.

Fig. 12. Measured temperature from the embedded sensor and from an external thermocouple versus the string current, $I_s$, with the thermal control loop disabled.

Fig. 13. Waveforms during the normal commutation process with PFM/PWM control with $T_l = 2$ s, $T_c = 14$ s. Smooth crossover is achieved with no discernible flicker. (Time scale: 5s/div)

longer $T_c$ will also allow a reduction in $T_j$ due to the increased thermal capacitance. The choice of $T_c$ ultimately depends on the application and the tolerable visible disturbance.

The electrical waveforms for the normal commutation process with PFM and PWM mode, and key waveforms for current balancing cycle are shown in Fig. 14 and Fig. 15. In Fig. 14(a), each string of Set a is sequentially turned on and balanced, while the corresponding string in Set b is turned off to maintain a constant illumination. The automatic adjustment of the $V_{gs,(1-3)a}$ is shown in Fig. 14(b). The detailed timing during balancing is shown in Fig. 15. The calibration starts at $t_1$. The DAC is held constant during $t_3 - t_4$ to allow the current loop to stabilize. From $t_4 - t_5$, $V_{GS,1a}$ is adjusted to achieve $V_{bus,a} = V_{bus,a}''$. The eleven strings have been balanced by $t_5$, at which point the string whose DAC has the highest setting (string 3a in this case) is enabled and set to the maximum value to update the voltage reference $V_{bus,a}''$ during $t_5 - t_6$. The second balancing stage occurs during $t_6 - t_{10}$, as described in Section III. Finally, all strings are disabled when the balancing is complete and the converter enters PFM mode at $t_{10}$. 
VI. CONCLUSIONS

The proposed LED commutation and string current balancing was verified experimentally. Smooth commutation is achieved, without any noticeable optical flicker. Further work is required to scale up the power converter by 4× for a full luminaire. In addition, more detailed characterization is needed to calibrate the thermal capacitances in the system model to the real system, in order to determine the best commutation frequency. If the thermal system near the LED case has sufficient thermal capacitance, a high commutation frequency can reduce the peak junction temperature and improve the LM70 lifetime by 5 months per 1°C. The redundancy in the system is exploited to perform on-line current balancing, without requiring more than one current sensor and without significantly disturbing the optical output. The new architecture is promising for industrial applications, where the high cost of lighting outages and regular maintenance justifies the incremental cost of the controller.

REFERENCES


