AC 2007-3098: UNDERGRADUATE SENIOR RESEARCH PROJECT TO DEVELOP A COMPUTER-CONTROLLED POWER SUPPLY FOR LEDS

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Undergraduate Senior Research Project to Develop a Computer Controlled Power Supply for LEDs

Abstract

This paper describes an active senior research project which is sponsored by the California Energy Commission under an Energy Innovation Small Grant Program (EISG). The goal of the research project is to establish and demonstrate the feasibility of producing a computer controlled power supply for large light emitting diode (LED) arrays. This is an endeavor to reduce energy consumption and costs compared to standard devices presently in use. These large arrays can consist of several thousand LEDs. The proposed investigation is directed at confirming the feasibility of designing an advanced computer controlled power supply for large parallel arrays of LEDs. It will control both the current and voltage being applied to the LED array. The investigation will endeavor to optimize the light effectivity, power consumption, and cost effectiveness for both daytime and nighttime operation.

Introduction

A senior project has been established to give students the opportunity to participate in real life research that is applicable to energy conservation in the State of California. This project will provide a capstone educational experience for senior students to enhance their ability to be initially productive professional engineers. The project team consists of three faculty in the Electrical and Computer Engineering (ECE) Department and four senior students. This project is due to be completed by the fall of 2007. This project will endeavor to establish and demonstrate the feasibility of producing a computer controlled power supply for large light emitting diode (LED) arrays. It will reduce energy consumption and costs compared to standard devices presently in use. These large arrays can consist of several thousand LEDs. It will control both the current and voltage being applied to the LED array. The investigation will endeavor to optimize the light effectivity, power consumption, and cost effectiveness for both daytime and nighttime operation. Major manufactures of LED arrays use series regulators which inevitability loose power in the Thevenin resistance in series with the LED array

The student research will include the development, test, and comparative evaluation of alternate prototype LED circuit topologies. Parameters such as power factor (pf), conversion efficiency (η), total harmonic distortion (THD%), spectral illumination (Lumens), device temperature, and temperature degradation (Lumens/^{o}C) will be measured.

Project Goals:

- Determine the feasibility of developing a low-cost computer controlled highly efficient power supply and controller for large LED arrays.
- Determine the feasibility of increasing the half- life of LEDs in large arrays.
- Determine the feasibility of developing a circuit topology which will increase circuit efficiency by 20%.
- Determine the feasibility of a low cost circuit topology that maintains high contrast ratios as energy consumption is reduced during night operation.

Project Tasks	Performance/Cost Objectives
Develop and computer simulate different circuit topologies	
Optimize a candidate circuit topology and then re-simulate to verify operation.	Demonstrate that the chosen circuit topology theoretically meets the design criteria stated in the goals
Design and fabricate circuit boards.	
Test a prototype LED array the same size as commercial traffic signals (approximately 200 LED array) using the candidate circuit topology. Measure power conversion efficiency (η), power factor (pf), temperature degradation (Lumens/^{o}C), spectral illumination (Lumens), and luminous efficacy (L/W). Compare measurement results between test circuit and commercial traffic signals.	- Demonstrate that the circuit topology is capable of reducing power consumption by 20% - Demonstrate that the circuit topologies reduce the 24-hour root mean square (rms) junction temperature by 20%. - Demonstrate that the circuit can operate at both minimum and maximum voltages established by local utilities. Demonstrate that the different circuit meets the requirements of existing standards such as the Federal MUTCD 2003 (Manual on Uniform Traffic Control Devices) and the MUTCD 2003 California Supplement, Sections 9-00 through 9-05.
Develop test protocol	Demonstrate that the test protocol detects defective out of compliance circuit boards.

State-of-the-Art

Many of the leading manufacturers of solid-state specialty circuits are competing to gain market share in the growing LED market. There are over 30 Companies competing in this market[2,10]. The LED driver circuits manufactured by these companies do no address the use of multiple LEDs exceeding several hundred to several thousand LEDs in a single circuit. Simple advertising signs that provide time and temperature use over 2000 LEDs, see Figure 1. The sign in Figure 1 uses series resistors that consumed considerable power. The goal of this project is to minimize or eliminate the series resistors. For example the drive circuits sold by Maxim Inc. are designed to provide power to less than 10 LEDs, see Figure 2.

Figure 1. Typical Commercial Time and Temperature Sign. Source: Designed and Constructed by Cal Poly Pomona University Students and the Project Team.
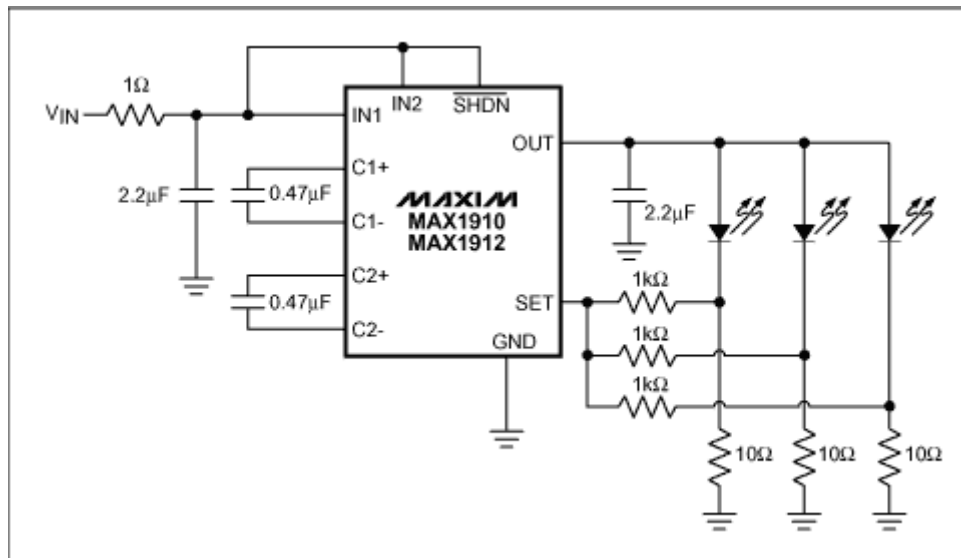

Figure 2. Typical Commercial LED Driver IC Block Diagram. Source: Maxim Corp.

To meet the requirements for large circuits starting with traffic lights, manufacturers are using simple series circuits and combinational series and parallel circuits which have a serious drawback[4]. Large strings of LEDs can fail to illuminate when only one LED fails. This is the familiar failure mode that

everyone equates to the old Christmas tree string of lights.   One light fails and they ALL go off.   This phenomenon is readily visible in many of the present LED traffic lights see Figure 3. This type of failure can be eliminated by inserting a series resistor with each LED and operating them in parallel. However, this circuit topology results in greatly reduced circuit efficiency. That is, it takes considerably more power for a given amount illumination because each resistor can consume more power than the LEDs themselves.
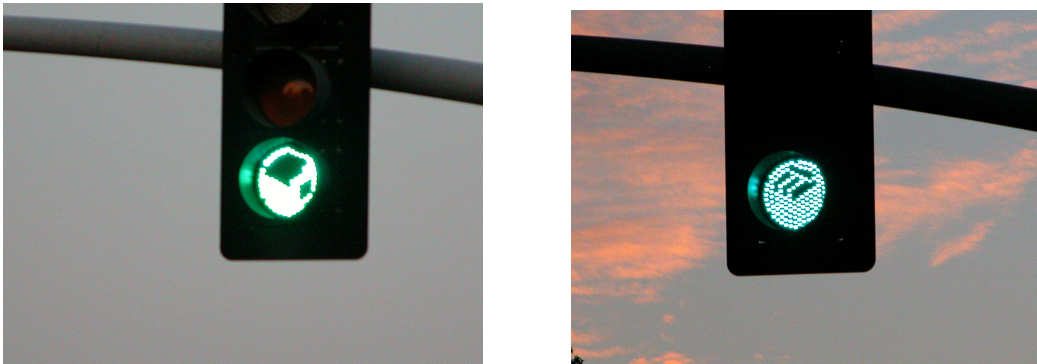

Figure 3. Sample Traffic Light Failures

A sample calculation shows just how inefficient this type of circuit topology can be. Suppose that we assume that we drive three parallel LEDs from a fixed 5-Volt source and limit the current to 20 mA in each LED.   Also assume that the voltage drop across the LED is 2.6 V at 20 mA. See Figure 4.
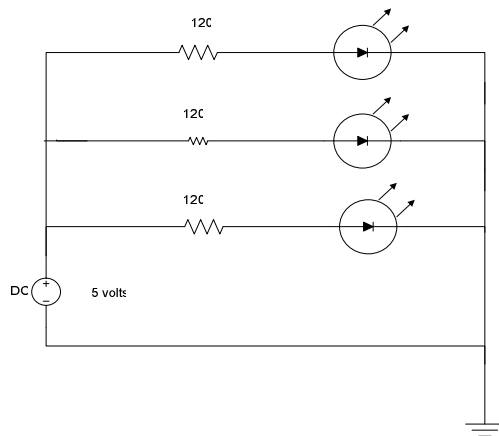

Figure 4. Simplified Parallel Power Circuit

$$\text{Power lost in each resistor } = i^2 R = 0.02^2 * 120 = 0.048W$$

$$\text{Power to each LED = IV=0.02*2.6=0.052W}$$

$$\text{Efficiency } = \frac{\text{Power to LED}}{\text{Power In}} = \frac{3*0.052}{0.060*5} = 52\%$$

This simple calculation shows that for parallel LED arrays the loss in the series resistor is very close to the power consumed by the LED and the efficiency is very low.

Determining the feasibility of eliminating these losses is a major thrust of this senior research project. Comparison measurements will be made to determine power consumption, illuminance efficacy, power factor, failure mode, and chrominance of a large LED array. The array will contain the same number of LEDs as a large traffic signal (approximately 100 LEDs). That is, traffic lights purchased from leading manufacturers will be used as a base for comparison. These test results will be evaluated by our industrial partner, International Rectifier Corp., to determine relative costs savings and manufacturability. If the feasibility results are positive then this data can be used to influence market place acceptance which when implemented will result in substantial savings to the State of California rate payers.

Students measured LED parameters at different temperatures using a Keithley 2520 precision current source and a temperature controlled LED holder.

Energy Problem Targeted

Reports to the Energy Commission have estimated that the annual power consumed at traffic intersections alone not including advertising signs is greater than 12 GWh/year[6]. It has been estimated[7] that approximately 3 billion kWh of energy could be saved nationally by converting all incandescent traffic signal to LEDs. This equates to enough energy to supply 24,000 households /month for traffic signal alone not including advertising signage. Energy savings for LEDs versus red neon signs is approximately 20% per the U.S. Small Business Administration[13]. The electric signage business in the United States is over $9 billion/year which encompasses small single handcrafted signs to mass produced signs.

Technical Feasibility Issues

Device to device variations in LEDs with the same part number will influence the feasibility of developing a circuit topology for the voltage and current feedback loops so as to minimize the losses that will occur in any series resistor. These

variations are being measured at the beginning of the project. Since manufacturing tolerances have greatly improved, there is a high degree of confidence that an optimum circuit topology can be obtained to achieve the stated goals. Measurements such as voltage, current, and power to the LED array will be performed as different feedback topologies are being investigated. Similar measurement will be made on commercially available traffic lights. These values from the traffic lights will be the base-line values used to establish feasibility. Achieving major energy savings will be shown if the measurement of power for the test circuit are significantly lower than the base-line values obtained for commercial traffic lights. The energy savings measured for the traffic lights can easily be extrapolated to large LED arrays consisting of several thousand LEDs.

Theoretical Discussion

A short theoretical discussion follows in order clarify some of the technical issues that will be addressed by this research. At steady-state, the light emitted by an LED is a simple function (very close to linear) of the current. The connection between the current and the emitted optical power comes from simple quantum physics principles: spontaneous light emission is proportional to the number of "occupied excited states" in the active region of the device. (In general, you also have to consider the empty terminal states for the photon emission event, but that's not a problem in LEDs.). Thus, controlling light intensity by controlling current is very simple: setting the current sets the light intensity.

The voltage across an LED under quasi steady-state operation at a particular light intensity (bias current), depends fairly strongly on the junction temperature in the active region and the band gap of the specific material used to make the device. Although the material is pretty much the same for each color of LED, the band gap (and therefore the exact spectrum of the light) also depends on the junction temperature, but the junction temperature is a quantity you can't measure directly. In fact, measuring the voltage change at constant current as an LED is turned on is often used as an easy way to estimate the junction temperature as a function of time. This temperature dependence represents a major complication for developing control laws, because the junction temperature is a function of the environmental temperature, the thermal conductivities of the various structures inside the packaged LED that provide the thermal connection between the active region and the external environment, and the past history of the electrical power converted to heat in the junction. That means the parameters in the control algorithm have to be adjusted for each color, manufacturer, and package.

That's all at quasi steady-state. But there are significant turn-on and turn-off transients associated with pulsing an LED (or any other diode) on and off. At turn-on, you have to "fill up" the depletion region with excess carriers, which is influenced by the junction capacitance, and you have to remove those excess carriers to turn the device off. The variable impedance of an LED thus also leads

to challenges in controlling the light emitted from any one LED in a distributed system because the states of the rest of the devices driven from a common power bus can have an important effect on the effective source impedance seen by that LED as a function of time.

These theoretical considerations will offer many challenges to the design team as they consider various circuit topologies to solve the problem of powering large LED arrays. Our initial effort will be to monitor current even though that requires some series resistance. The reason is that a measurement of the light output will be very difficult to implement, especially with the high-brightness LEDs, at low complexity and cost. (High-brightness LEDs, which are really high-efficiency LEDs, get their improved performance by directing almost all of the light emitted by the junction into the output.) That's great because it improves their conversion efficiency from about 2% to more like 8%. But that's bad for measuring light intensity at the mounting socket, because the improvements in efficiency are obtained by virtually eliminating this stray light.

In order to keep the control algorithms simple, we will look at some of the "power factor control" methods used with large motors and some switching power supplies. That way, we can limit the distributed interactions between LEDs and ensure that simple control algorithms can be guaranteed to be stable in systems with arbitrary numbers of LEDs.

In order to reduce the power lost to the series resistances in the power distribution lines, we will consider ways to stagger the PWM pulses to diodes or groups of diodes to keep both average and peak currents low. This is another place where power factor control would help. Intuitively the out-of-phase currents from the collective capacitances of all these diodes might be non-trivial, so that minimizing them will reduce the power factor related losses in the overall system. Just how trivial will be addressed in the initial computer simulations.

Proposed Innovations

This proposal will incorporate a circuit topology that will determine the feasibility of eliminating series resistors and the high voltage required by series connected LEDs. It will also determine the feasibility of driving large parallel arrays of LEDs using feedback loops to control voltage, current, and power from a computer controlled power supply. A block diagram of the system is shown in Fig. 5. The circuit topology will consist of a computer which outputs a control signal to a Pulse Width Modulated (PWM) power supply which outputs a controlled voltage to the LED array. The computer will hold the control algorithm developed during this research. This algorithm will require current inputs from several locations in the LED array. Resistors R1 and R2 perform this function. The research will also determine the number of required feedback signals. The algorithm will also require the output voltage and the temperature of

the LED array as inputs (feedback signals). As shown in the diagram there are five feed back signals, voltage, current (2), and temperature (2). Filter circuits such as the LC shown will be added as necessary. Notice that the output to a traffic light will be amplified so as to be compatible with existing traffic controllers which detect when a light fails. Because of the very small current output by the computer, this signal will have to be amplified. This same signal may have other uses depending upon the end use of the LED array. Coming into the computer is the operating setpoint such as luminance of the LED array. This signal can be input either manually or controlled by the computer algorithm. The setpoint might, for example, be the time from an astronautical timer which determines when an array will be dimmed to save energy. This same function could also be performed using a photoelectric feedback signal. The innovation of this approach is to minimize (preferably eliminate) any resistor in series with the individual LEDs and/or the complexity of controlled current sources in series with each LED.
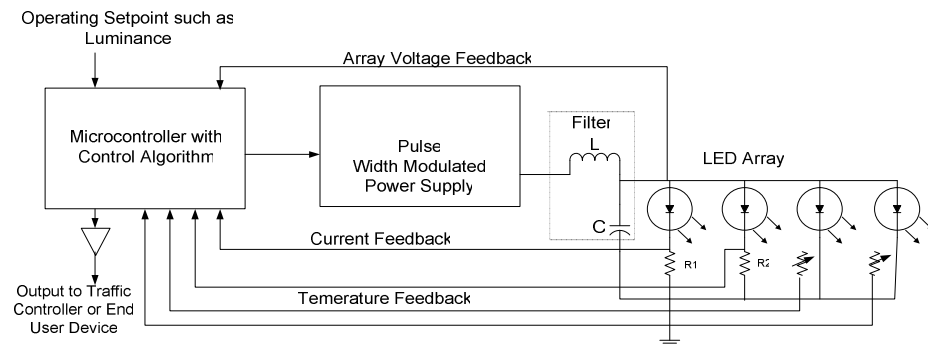

Figure 5. System Block Diagram

Impact on Energy Problem / Benefit to California electric market

Initial theoretical calculations show that it should be feasible to reduce the power consumption by as much as 40% for existing LED systems and 95% for existing incandescent systems. This equates to approximately 7.1 GWh/yr based on power consumption for all intersections[6,9] The energy saved on signage is estimated to be 5 to 10 times this amount. The use of LEDs in traffic signals, signs, and displays has continued to increase dramatically. The energy consumption and resultant savings would be correspondingly significantly increased. This magnitude of energy and associated cost reduction will be attractive for end users and constitute an incentive for commercial product developers. The demonstration of these energy savings resulting from this project will provide strong confidence for the evolution from this applied research project to commercial design, implementation and end use application.

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