Briefing Notes

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LED Electronic Control Circuits for Off-grid Lighting Products

This Briefing Note introduces basic concepts in electronic design for low power off-grid lighting products and suggests ways to improve power efficiency. It is intended for manufacturers and engineers. This Briefing Note builds on previous Notes from Lighting Africa available at:

http://www.lightingafrica.org/resources/briefing-notes.html

Introduction

The LED driver, or ballast, of a modern off-grid lighting product is responsible for regulating power from the battery to the LED or LED array. There are many designs for LED drivers, and each has advantages and disadvantages in terms of efficiency, cost, and performance. LED drivers are available as prepackaged integrated circuits (ICs) or may be built with discrete components. The term "LED Driver" can refer to the entire circuit design, a specific topology, or an IC that requires external components to set performance values. This briefing note will introduce LED driver basics and discuss typical LED driver topologies commonly used for off-grid lighting products.

LED Electronic Basics

LEDs are semiconductor diode devices. Electric current flows through an LED in one direction only, from the device anode to the cathode. When a positive voltage is applied to the anode, current will flow and light is emitted; this is called 'forward biasing' the diode. The amount of current is dependent on the specific material of the LED chip and the voltage level – higher voltages produce more current and light output.

LEDs are grouped into forward voltage (V_F) 'bins' by the LED manufacturer. LEDs from any single bin have a range of forward voltages, with a typical forward voltage for white LEDs being near 3.6V.

When an LED is forward biased (turned 'ON') with a constant voltage source, the LED chip will begin to heat up. This shifts the diode forward voltage curve, causing more current to flow and further increasing the temperature (Figure 1).

This **thermal runaway** can potentially damage the LED or lower its lifetime, and must be controlled by implementing some type of current or voltage regulation.

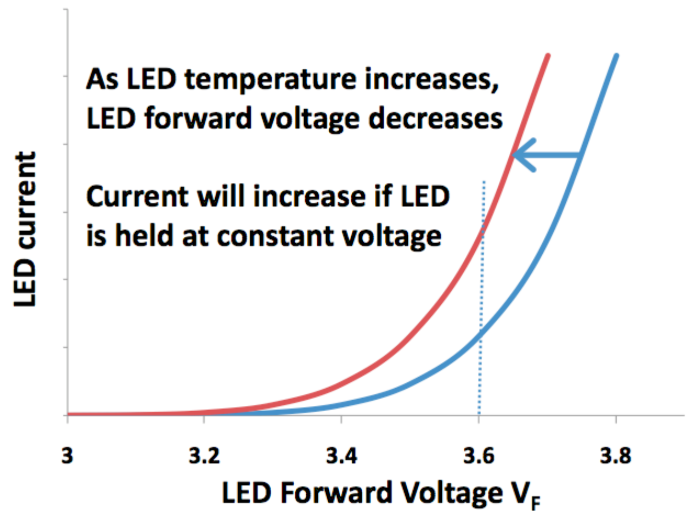

Figure 1. LED thermal runaway

Constant Voltage vs. Constant Current

LED drivers deliver power to the LED by either regulating the voltage (constant voltage) or current (constant current). Constant current drivers are generally considered a better choice, as these have some mechanism to monitor the current through the LED and prevent over-current situations from arising.

LED Driver Topologies

The details of LED electronic control circuits vary widely. Three broad categories cover most applications: current limiting resistive, linear, and switching type drivers. The choice of driver topology will depend on many factors including LED type and power, cost, and additional circuit features such as auxiliary cell phone charging.

Series/Parallel LED Array Configurations

Systems with multiple LEDs will run the LEDs in series, parallel, or a series/parallel combination (Figure 2). The choice of configuration is dependent on the input battery voltage, the driver selection, and the overall power level. Because of the voltage tolerances inherent in the LEDs, parallel arrays may have current balancing problems where some LEDs run at higher currents and consume more power. These LEDs will then run at higher temperatures and may have lower lifetimes. To avoid this problem, current balancing resistors can be placed in series with each LED string.

Resistive Current Limiting

The most basic type of LED driver places a current limiting resistor in series with the LED or LED string. The resistor value must be high enough to compensate for the forward voltage tolerance of the LEDs, but low enough to prevent excessive power loss. This circuit will be the least expensive to produce but is relatively inefficient and also has a wide operating tolerance. The delivered LED power will be inconsistent from circuit to circuit and as a result the light output from product to product will vary widely.

Linear Regulators (linear current sources)

Linear regulators control the LED current by using a series transistor operated in the linear region (Figure 3). This means that the transistor is operating as a variable resistor, adjusting its resistance to maintain a set current or voltage. As such, linear regulators can be configured as constant current devices and have the advantage that they control LED current (and power) to a precise value.

Careful matching between regulator input and output voltages is necessary to keep power loses minimized. Heat sinking the regulator or transistor is also typically required to dissipate the generated heat.

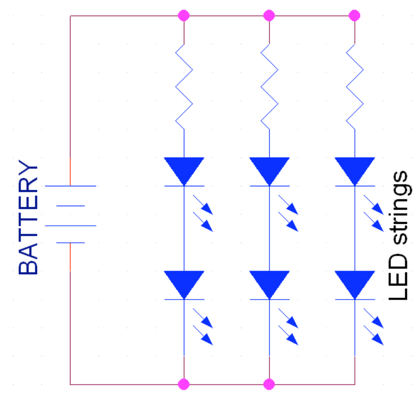

Figure 4. Series/Parallel LED Array with Current Balancing Resistors

Key Features

- V (batt) > V (led)
- Very low cost
- Simple circuit design / low component count
- Poor current regulation
- Low efficiency

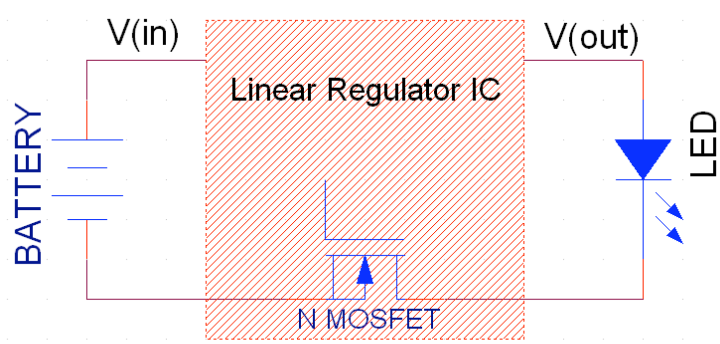

Figure 3. Linear Regulator

Key features

- V (in) > V (out)
- Low cost
- Simple circuit design / low component count
- Accurate LED constant current
- No EMI switching noise
- May require additional heatsinking
- Careful voltage matching necessary to achieve adequate efficiency
- Moderate to low efficiency

Switching Regulators

Switching topologies efficiently transfer energy from one voltage level to another by switching power through an inductor or other magnetic component. For LED systems, they are typically configured as constant current devices and regulate current by monitoring the voltage drop through a 1% (or better) low ohm series sense resistor R(sense). Switching regulators are capable of 95% or better efficiency under certain circumstances.

Buck (step-down) Regulators

A buck regulator (Figure 4) starts by turning on a transistor (usually an N-type or P-type mosfet) that allows current to flow through the inductor/LED current path. Current will ramp up as the inductor is charged, and when the feedback voltage on R(sense) reaches a certain level the control turns off the transistor. Energy stored in the inductor continues to drive the LED current, using the freewheeling diode as a return path. As the inductor current falls back down, the control switches on the transistor again and the cycle repeats.

Current in the inductor/LED path ramps up and down; both peak and average values must be considered when choosing components. The switching frequency, a key metric, influences the inductance value and peak current. Higher switching frequencies result in smaller components due to lower peak currents.

Boost (step-up) Regulators

Boost regulators (Figure 5) drive higher output voltages and are used with LED strings where V(led)>V(batt). Instead of using a buck regulator's freewheeling diode, they use a clamping diode in line with the inductor to capture the inductor energy and place an output capacitor in the circuit to supply the LED(s) during the off stage of the switching cycle. As with a buck regulator, current will ramp up and down in the inductor and LED, with average and peak values.

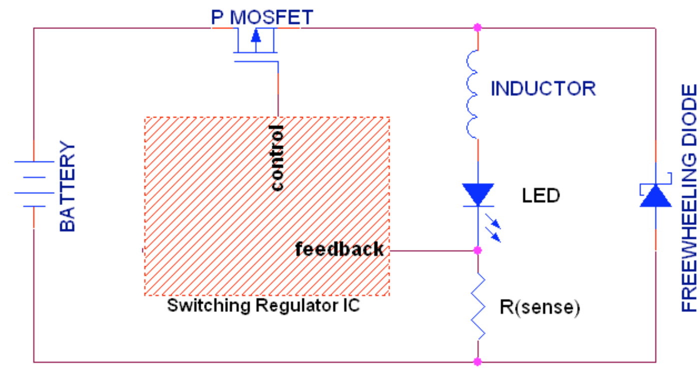

Figure 4. Switching (BUCK) Regulator

Key Features

- V(batt) > V(led)
- Can be very efficient
- Accurate LED constant current
- High component count
- Relatively complex
- EMI switching noise

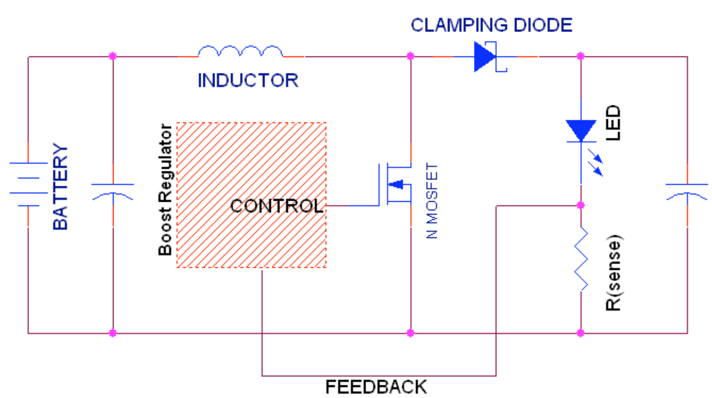

Figure 5. Switching (BOOST) Regulator

Key Features

- **V(led) > V(batt)**
- Can be very efficient
- Accurate LED constant current
- High component count
- Most complex
- EMI switching noise

Buck-Boost Regulators

Buck regulators require V(batt)>V(led), and boost regulators require V(batt)<V(led). Buck-boost regulators are used when the input battery voltage fluctuates above and below the LED voltage, and are capable of transitioning the output voltage stage to maintain current regulation.

Synchronous Rectification for Switching Drivers

Advanced designs for switching circuits replace the freewheeling and clamping diodes with transistor switches. This lowers the diode losses associated with forward biasing these components. Low ON resistance transistors should be used. These elements are often incorporated directly into the driver IC.

Driver Efficiency

Many factors influence the efficiency of LED drivers. Driver type, component selection, and printed circuit board (PCB) layout design are all critical elements and must be properly integrated to ensure that the system performs to expected efficiency levels.

Design Tips for Efficient Driver Performance

- Use switching drivers for maximum efficiency.
- Electronic components should be sized to handle peak, not average, currents.
- Avoid electrolytic capacitors. Use ceramic chip or tantalum capacitors with low ESR (equivalent series resistance) values.
- PCB layouts should include heavy, short traces to connect components along the main current paths and heavy wire gauges to connect components
- Place the inductor, capacitors, and switching transistor as close together on the PCB as possible. Follow the IC manufacturers guidelines on ground connections to avoid ground current loops and regulator instability.

Electronic Switching "Noise"

Switching circuits often generate electromagnetic interference (EMI) that can be emitted as radiation or as electronic noise conducting through the wires connected to the system. This can interfere with the internal regulation of the device OR cause problems with nearby electronic devices. FM radio reception in particular may be adversely effected and can often be detected while listening to a radio and turning the LED driver ON and OFF. Careful design and the use of noise filter components are sometimes necessary to mitigate EMI problems.

Dimming Control Schemes

Multiple light output levels are often used with off-grid lighting products to increase battery run times. The two primary ways to 'dim' an LED array include reducing the current in the array (linear, analog dimming) OR pulsing the LED at high frequencies (100+ Hz to several kHz).

Most LED manufacturers recommend pulse width modulation (PWM) techniques to dim LEDs. This turns the LEDs ON and OFF at frequencies high enough to avoid the appearance of flicker in the light output. PWM dimming is very efficient, avoids resistive power losses associated with linear dimming, and maintains high tolerances on LED light output and color shift.

Conclusion

Careful selection, design, and testing of the LED driver is crucial to ensuring the lighting product performs consistently and delivers the correct amount of power, and light output, from the LED(s). As with other components of an off-grid lighting product, the driver is an essential element that must operate properly for the product to work. The added cost of increasing the driver's efficiency can pay for itself with savings in other components (such as a smaller battery and solar panel) and provide additional benefits including increased product lifetime and user satisfaction.