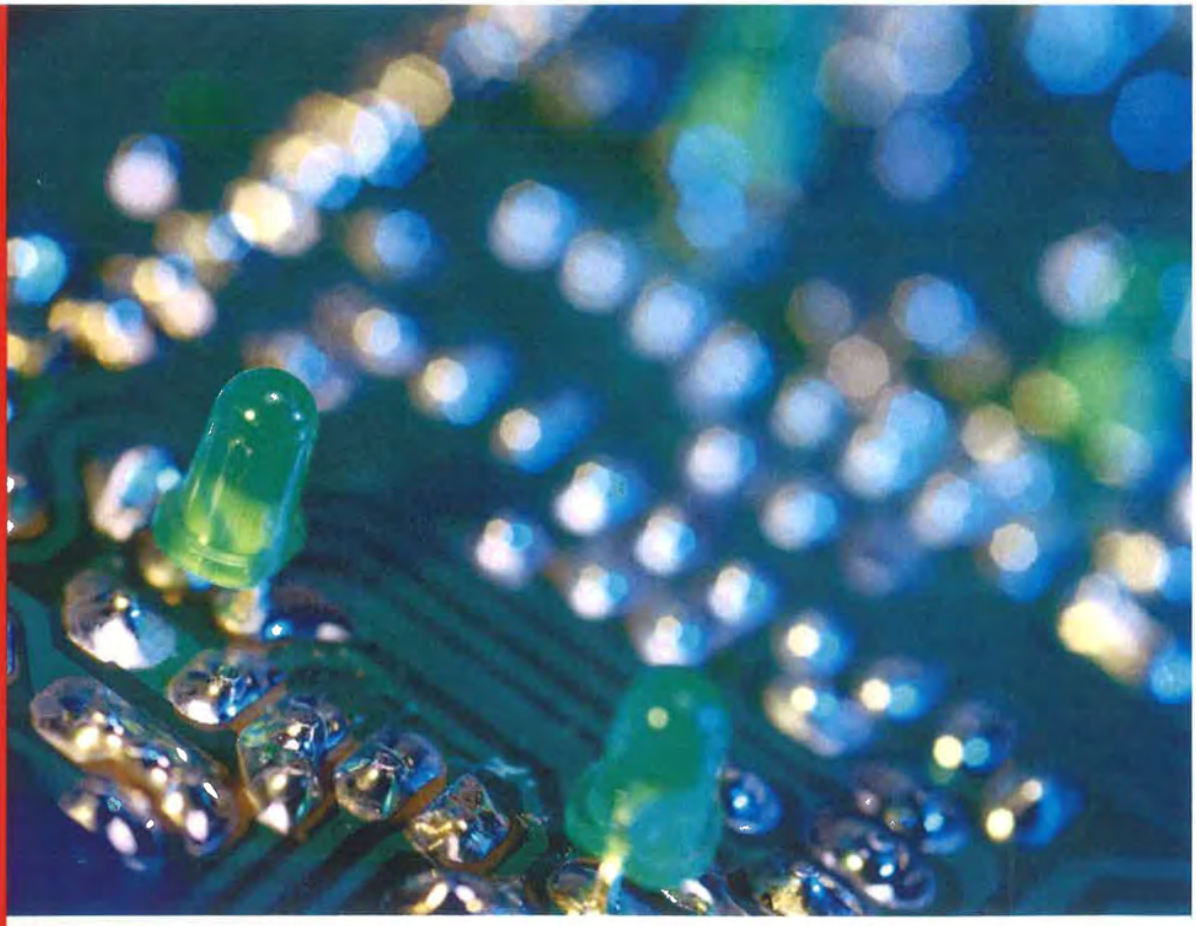

Power Supplies for LED Driving

Steve Winder

Newnes

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30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Library of Congress Cataloging-in-Publication Data
Application submitted

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

ISBN: 978-0-7506-8341-8

For information on all Newnes publications
visit our Web site at www.books.elsevier.com

Printed in the United States of America
08 09 10 11 12 13 10 9 8 7 6 5 4 3 2 1

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Preface

The LED has been available for many years now, initially as a red colored indicator. Later, yellow/amber, green and finally blue colored LEDs became available, which triggered an explosion in applications. Applications included traffic lights, vehicle lights and wall-washes (mood lighting). Recently blue colored LEDs have been combined with yellow phosphor to create white light. The amount of light available from LEDs has also increased steadily, and now power levels of 1 W, 3 W and 5 W are fairly common.

Driving a single LED, or a long string of LEDs connected in series, has relatively few problems when the current is low (may be 20 mA). High current LEDs are tougher to drive, requiring 350 mA, 700 mA, 1 A or higher. Of course, a simple linear regulator could be used if power dissipation was not an issue, or a simple resistor if current regulation is not critical. However, in most applications, an efficient switching regulator is used. A switching regulator is essential if the LED string voltage is higher than the supply voltage, or if the supply voltage has wide variation. But switching means that electro-magnetic interference (EMI) has to be considered too.

This book describes a number of LED driving methods. The main aims of this book are: (1) to show suitable types of LED driver topologies for given applications; (2) to work through some examples; and (3) to avoid some of the mistakes that some engineers make when creating their own designs. However, the content is not exhaustive and further reading in some peripheral topics will be necessary.

Significant data to create this book have been drawn from the datasheets, application notes, training material and discussions provided by my colleagues in Supertex, particularly Rohit Tirumala and Alex Mednik.

Steve Winder, 2007.

CHAPTER 1

Introduction

As a field applications engineer for one of the pioneering developers of integrated circuits for driving power LEDs, I meet many potential customers who have little or no idea of how to drive an LED properly. The older type of LED requiring a 20 mA supply can be abused to some extent. However, power requirements have been increasing; current ratings of 30 mA, 50 mA, 100 mA, 350 mA and higher are becoming common. There are several manufacturers that produce power levels up to 20 W, and more; these higher powers use LED chip arrays. If a power LED is abused, it tends to die very quickly.

Power LEDs are being used in increasing numbers; in channel lighting (signage), traffic lights, street lights, automotive, mood lighting (colour changing 'wall wash'), theatre lighting for steps and emergency exits. Names such as HB-LEDs (high bright) and UB-LEDs (ultra-bright) are becoming meaningless as the power levels continue to rise. This book will cover all types of LED drivers, from low power to UB-LEDs and beyond.

Is power LED driving simple? No, not usually. In a few cases a linear regulator can be used, which is simple, but most cases require a switching power supply with a constant current output. Linear driving is inefficient and generates far too much heat. With a switching supply, the main issues are EMI and efficiency, and of course cost. The problem is to produce a design that meets legal requirements and is efficient, with minimal cost.

1.1 Objectives and General Approach

The approach of this book will be very practical, although some theory is introduced when necessary for understanding of later chapters. It is important to understand the characteristics of components before they can be used effectively.

In most chapters, I will include a section called 'Common Errors'. This section will highlight errors that engineers have made, and how these can be avoided, with the hope that readers will not make the same mistakes. It is said that people learn from their mistakes, but it is also true that we can learn from the mistakes of others. Our own mistakes are more memorable, but also more costly!

Usually the first problem for a designer is to choose between different topologies. When is a buck preferred to a buck-boost or a boost? Why is a Cuk boost-buck better than a fly-back type? This book will cover these topics at the beginning of the switching supplies section.

Power supply design equations will be given and example designs of practical supplies will be worked through. With switching power supplies, equations are needed to make the correct component choice; a wrong component can make a poor power supply and require a lot of corrective action. Power LEDs generate a lot of heat in a small area, which makes thermal management difficult, so an adjacent power supply should be efficient and not add too much heating effect.

The implications of changing the calculated component values into standard values, which is more practical, will be discussed. In many cases, customers want to use standard off-the-shelf parts, because of ease of purchase and cost. Calculations rarely produce a standard value, so a compromise has to be made. In some cases the difference is negligible. In others it may be better to choose a higher (or lower) value. All component value changes will introduce some 'error' in the final result.

Having proven worked examples in the book will help the reader to understand the design process: the order in which the design progresses. It will also show how the calculated component value compares with the actual value used, and will include a description of why the choice was made.

1.2 Description of Contents

In Chapter 2, the description of some LED applications will show the breadth of the LED driving subject and how LEDs' physical characteristics can be used to an advantage. It is also important to understand the characteristics of LEDs in order to understand how to drive them properly. One of the characteristics is colour; an LED emits a very narrow band of wavelengths so the colour is fairly pure. The LED color determines the different voltage drop across the LED while it is conducting, and I will

show how that varies with the current level. But the current level determines the light output level: higher currents give higher luminosity from a given LED. The light output has the characteristic of intensity and the amount of beam spreading.

Chapter 3 will show that there are several ways to drive LEDs. Because most electronic circuits have traditionally been driven by a voltage source, it is natural for designers to continue this custom when driving an LED. The trouble is that this is not a good match for the LED power requirement. A constant current load needs a constant voltage source, but a constant voltage load (which is what an LED is) needs a constant current supply.

So, if we have a constant voltage supply, we need to have some form of current control in series with the LED. With a series resistor or active regulator circuit we are trying to create a constant current supply. In fact, a short circuit in any part of the circuit could lead to a catastrophic failure so we may have to provide some protection. Detecting an LED failure is possible using a current monitoring circuit. This could also be used to detect an open circuit. Instead of having a constant voltage supply, followed by a current limiter, it seems sensible to just use a constant current supply! There are some merits of using both constant voltage supply and a current regulator, which will be described in Chapter 4.

Chapter 3 continues describing features of constant current circuit. If we have a constant current source, we may have to provide some voltage limiting arrangement, just in case the load is disconnected. Open circuit protection can take many forms. A failure (short) would make no difference to the current level, so voltage monitoring would be a preferred failure detection mechanism. If the circuit failed open the voltage would rise up to the level of the open circuit protection limit, which could also be detected.

Chapter 4 describes linear power supplies, which can be as simple as a voltage regulator configured for constant current. Advantages include no EMI generation, so no filtering is required. The main disadvantage is heat dissipation and the limitation of having to ensure that the load voltage is lower than the supply voltage; this leads to a further disadvantage of only allowing a limited supply voltage range.

Chapter 5 describes the most basic of switching LED drivers: the buck converter. The buck converter drives an output that has a lower voltage than the input; it is a step-down topology. The reader will be taken through the design process, followed by an example design.

Chapter 6 describes boost converters. These are used in many applications including LCD backlights for television, and computer and satellite navigation display screens.

The boost converter drives an output that has a higher voltage than the input; it is a step-up topology. The reader will be taken through the design process, followed by an example design, for both continuous mode and discontinuous mode drivers.

Chapter 7 describes boost-buck converters. These have the ability to drive a load that is either higher or lower voltage compared to the input. However, this type of converter is less efficient than a simple buck or boost converter.

Chapter 8 describes specialist converters: buck-boost and buck (BBB), and Bi-Bred. These converters are intended for AC input applications, such as traffic lights, street lights and general lighting. They combine power factor correction with constant current output, but in many cases can be designed without electrolytic capacitors and so are useful for high reliability applications. This extra functionality does come at a cost – the efficiency is much lower than a standard off-line buck converter.

Chapter 9 describes fly-back converters. This chapter describes simple switching circuits that can be used for constant voltage or constant current output. The use of two windings or more in an inductor permits isolation of the output. A single winding inductor is a non-isolated buck-boost circuit that is sometimes used for driving LEDs, although the Cuk and SEPIC generally produce less EMI (at the cost of an additional inductor).

Chapter 10 covers topics that are essential when considering a switch mode power supply. The most suitable topology for an application will be discussed. The advantages, disadvantages and limitations of each type will be analyzed in terms of supply voltage range and the ability to perform PFC (power factor correction). Discussion will include snubber techniques for reducing EMI and improving efficiency, limiting switch-on surges using either in-rush current limiters or soft-start techniques.

Chapter 11 describes electronic components for power supplies. The best component is not always an obvious choice. There are so many different types of switching elements: MOSFETs, power bipolar transistors and diodes, each with characteristics that affect overall power supply performance. Current sensing can be achieved using resistors or transformers, but the type of resistor or transformer is important; similarly with the choice of capacitors and filter components.

Magnetic components are often a mystery for many electronic engineers, and these will be briefly described in Chapter 12. First, there are different materials: ferrite cores, iron dust cores and special material cores. Then there are different core shapes

and sizes. One of the most important physical characteristics from a power supply design point of view is magnetisation and avoiding magnetic saturation.

EMI and EMC issues are the subjects of Chapter 13. It is a legally binding requirement that equipment should meet EMI standards. Good EMI design techniques can reduce the need for filtering and shielding, so it makes sense to carefully consider this in order to reduce the cost and size of the power supply. Meeting EMC standards is also a legal requirement in many cases. It is no use having an otherwise excellent circuit that is destroyed by externally produced interference. In many areas, EMC practices are compatible with EMI practices.

Chapter 14 discusses thermal issues for both the LEDs and the LED driver. The LED driver has issues of efficiency and power loss. The LED itself dissipates most of the energy it receives (volts times amps) as heat: very little energy is radiated as light, although manufacturers are improving products all the time. Handling the heat by using cooling techniques is a largely mechanical process, using a metal heatsink and sometimes airflow to remove the heat energy. Calculating the temperature is important because there are operating temperature limits for all semiconductors.

Another legal requirement is safety, which is covered in Chapter 15. The product must not injure people when it is operating. This is related to the operating voltage and some designers try to keep below SELV (safety extra low voltage) limits for this reason. When the equipment is powered from the AC mains supply, the issues of isolation, circuit breakers and creepage distances must be considered.

CHAPTER 2

Characteristics of LEDs

Most semiconductors are made by doping silicon with a material that creates free negative charge (N-type), or free positive charge (P-type). The fixed atoms have positive and negative charge, respectively. At the junction of these two materials, the free charges combine and this creates a narrow region devoid of free charge. This 'intrinsic region' now has the positive and negative charge of the fixed atoms, which opposes any further free charge combination. In effect, there is an energy barrier created; we have a diode junction.

In order for a P-N junction to conduct, we must make the P-type material more positive than the N-type. This forces more positive charge into the P-type material and more negative charge into the N-type material. Conduction takes place when (in silicon) there is about 0.7 V potential difference across the P-N junction. This potential difference gives electrons enough energy to conduct.

An LED is also made from a P-N junction, but silicon is unsuitable because the energy barrier is too low. The first LEDs were made from gallium arsenide (GaAs) and produced infrared light at about 905 nm. The reason for producing this color is the energy difference between the conduction band and the lowest energy level (valence band) in GaAs. When a voltage is applied across the LED, electrons are given enough energy to jump into the conduction band and current flows. When an electron loses energy and falls back into the low energy state (the valence band), a photon (light) is often emitted.
See Figure 2.1.

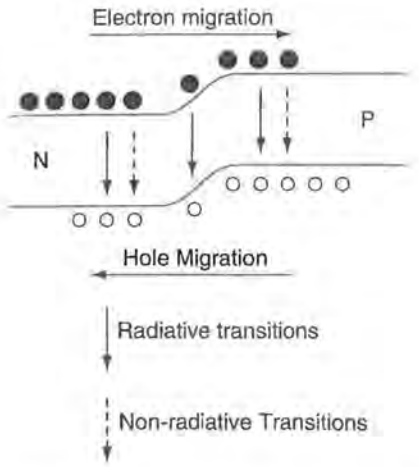

Figure 2.1: Band Diagram of P-N Junction Semiconductors.

2.1 Applications for LEDs

Soon new semiconductor materials were developed and gallium arsenide phosphide (GaAsP) was used to make LEDs. The energy gap in GaAsP material is higher than GaAs, so the light wavelength is shorter. These LEDs produced a red color light and were first just used as indicators. The most typical application was to show that equipment was powered, or that some feature such as 'stereo' was active in a radio. In fact it was mainly consumer products like radios, tape recorders and music systems that used red LEDs in large numbers.

When yellow and green LEDs became available, the number of applications increased. Now the color could change, to give additional information, or could indicate more urgent alarms. For example, green = OK, yellow = requires attention, red = faulty. Most important was the ability to have LED lamps in traffic lights.

One characteristic of the light from an LED is that it occupies a narrow spectrum about 20 nm wide; the color is fairly pure. By contrast, a semiconductor laser used for telecommunications occupies a spectrum about 2 nm wide. The very narrow spectrum of a laser is important because, when used with optical fiber systems, the narrow spectral width allows a wide system bandwidth. In general-purpose LED applications, the spectral width has very little effect.

Another important characteristic of LED light is that current is converted into light (photons). This means that doubling the current doubles the light amplitude. So

dimming lights by lowering the current is possible. It should be noted that the specified wavelength emitted by an LED is at a certain current; the wavelength will change a little if the current is higher or lower than the specified current. Dimming by pulse width modulation (PWM) is a viable alternative used by many people. PWM dimming uses a signal, typical frequency 100 Hz–1000 Hz, to turn the LED on and off. The pulse width is reduced to dim the light, or increased to brighten the light.

The 'holy grail' was blue LEDs, which are made from indium gallium nitride (InGaN). When adding colored light, red, green and blue make light that appears white to the human eye. The reason for only 'appearing' white is that the eye has receptors (cones) that detect red, green and blue. There are big gaps in the color spectrum, but the eye does not notice. White LEDs are sometimes made using blue LEDs with a yellow phosphor dot over the emitting surface. The yellow phosphor creates a wide spectrum and, when combined with the blue, appears white.

An interesting application for blue LEDs is in dentistry. Illuminating modern resins used in tooth filling materials with blue light will harden the resin. The 465 nm wavelength has been found to be close to optimum for this application, although the intensity of the light must be high enough to penetrate through the resin.

Some interesting applications rely on the purity of the LED color. The illumination of fresh food is better with LEDs, because they emit no ultraviolet light. Photographic dark rooms can use colors where film is insensitive – traditionally dark rooms have been illuminated by red colored incandescent lamps. Even traffic lights must emit a limited range of colors, which are specified in national standards.

It should be noted that the color of an LED would change as the LED's temperature changes. The temperature can change due to ambient conditions, such as being housed adjacent to hot machinery, or due to internal heating of the LED due to the amount of current flowing through it. The only way to control ambient temperature is to add a cooling fan, or by placing the LED away from the source of heat. Mounting the LED on a good heatsink can control internal heating.

The early LEDs were all rated at 20 mA and the forward voltage drop was about 2 V for red, higher for other colors; later low current LEDs were created that operated from a 2 mA source. Over time the current rating of LEDs has increased, so that 30 mA, 50 mA and even 100 mA are fairly common. Lumileds was created by HP and Philips in 1999 and produced the first 350 mA LED. Now there are a number of power LED manufacturers, rated at 350 mA, 700 mA, 1 A and higher. Power LEDs

are being used in increasing numbers; in channel lighting (signage), traffic lights, street lights, automotive, mood lighting (color changing 'wall wash'), and also in theaters for lighting steps and emergency exits.

Channel lighting is so called because the LEDs are mounted in a channel; see Figure 2.2. Typically this channel is used to form letters, for illuminated company name signs. In the past, channel lighting used cold-cathode or fluorescent tubes, but these had reliability problems. Health and safety legislation, like the RoHS Directive, banned some materials like mercury that is used in the construction of cold-cathode tubes. So, to cope with the shapes and environmental conditions, the most viable technology is LED lighting.

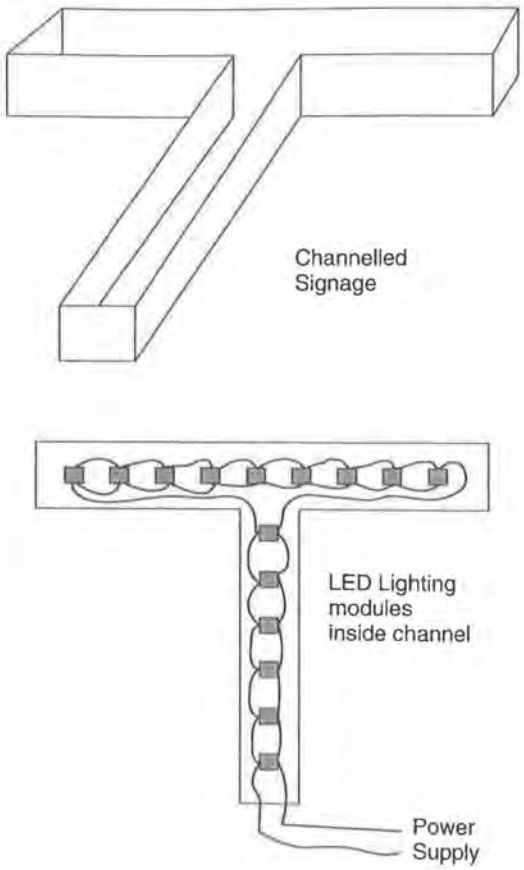

Figure 2.2: Channel Lighting.

Traffic lights have used low power LEDs for some years, but now some manufacturers are using a few high power LEDs instead. One problem with traffic lights is controlling the wavelength of the yellow (amber) light. Yellow LEDs suffer from a greater wavelength shift than other colors, and this can cause them to operate outside their permitted spectral range. Another problem is making them fail-safe – authorities permit some degree of failure, but if more than 20% of the LEDs fail, the entire lamp must be shut down and a fault reported to maintenance teams.

High ambient temperatures inside the lamp housing can lead to LED driver failures. This is particularly true if the LED driver circuit contains electrolytic capacitors, which vent when hot and eventually lose their capacitance. Some novel LED drivers have been developed that do not need electrolytic capacitors and can operate for several years at high temperatures. Failing LED drivers can give LED lights a bad name – why have LEDs that can work for over 100,000 hours if the LED driver fails after 10,000 hours' operation?

Street lights have been built using medium and high power LEDs. Although this would seem to be a simple application, high ambient temperatures and relatively high power LEDs can give rise to driver problems. In some cases, white and yellow LEDs are used together to create a 'warm-white' light. The problem with white LEDs, made using a blue LED and a yellow phosphor, is that the high blue content produces a 'cold-white' light.

Automotive lighting has many applications; internal lights, headlights, stoplights, daylight running lights (DRL), rear fog lights, reversing lights, etc. The greatest problem with automotive applications is that the EMI specifications demand extremely low levels of emissions, which are difficult to meet with a switching circuit. Linear drivers are sometimes used if the efficiency is not a critical requirement. Connecting a linear driver to the metal body of the vehicle can be used to dissipate the heat generated.

Automotive stoplights using LEDs have a significant safety advantage over those using filament lamps. The time from current flow to light output in an LED is measured in nanoseconds. In a filament lamp the response time is about 300 ms. At 60 mph (100 km/h), a vehicle travels 1 mile (1.6 km) per minute, or 88 feet per second. In 300 ms, a car will travel over 26 feet (8 meters). Stopping 300 ms sooner, having seen the previous car's brake lights earlier, could avoid death or injury. Also, LED brake lights are less likely to fail.

Mood lighting is an effect caused by changing the color of a surface and uses human psychology to control people's feelings. It is used in medical facilities to calm patients, and on aircraft to relax (or wake up!) passengers. Generally mood lighting systems use red, green and blue (RGB) LEDs in a 'wall wash' projector to create any color in the spectrum. Other applications for these RGB systems include disco lights!

Backlighting displays, such as flat screen televisions, also use RGB LED arrays to create a 'white' light. In this case the color changes little – ideally not at all. However, a control system is required to carefully control the amount of red, green and blue, to create the exact mix for accurate television reproduction. Cold cathode tubes are sometimes used to backlight computer screens, but here the exact color is not important.

2.2 Light Measure

The total light flux is measured in units of lumens. The lumen is the photometric equivalent of 1 watt, weighted to match the normal human eye response. At 555 nm, in the green-yellow part of the spectrum where the eye is most responsive, 1 W = 683 lumen.

The term candela is also used. This is the light produced by a lamp, radiating in all directions equally, to produce 1 lumen per steradian. As an equation, 1 cd = 1 lm/sr.

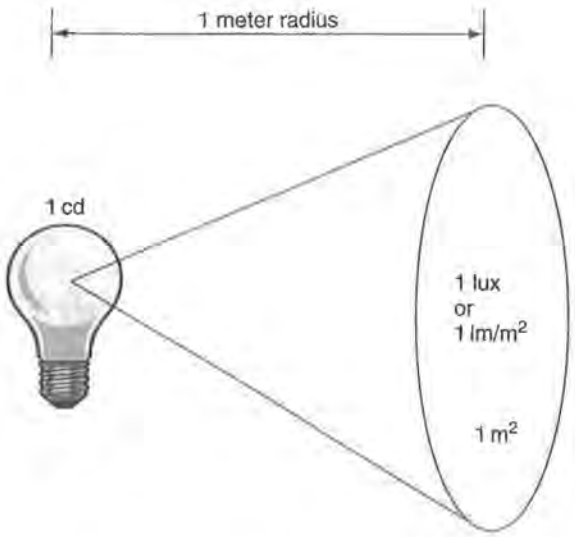

Figure 2.3: Light Measurement.

A steradian has a projected area of 1 square meter, at a distance of 1 meter from the light source. The light from a 1 cd source, at meter distance, is 1 lux, or 1 lm/m^2, see Figure 2.3.

Light emission efficiency (luminous efficacy) from LEDs is described in terms of lumens per watt. There is some competition between LED manufacturers to get the highest luminous efficacy, but when comparing results it is important to make a note of the electrical power levels used. It is easier to make an efficient 20 mA LED, than an efficient 700 mA LED.

2.3 Equivalent Circuit to an LED

An LED can be described as a constant voltage load. The voltage drop depends on the internal energy barrier required for the photons of light to be emitted, as described earlier. This energy barrier depends on the color; thus the voltage drop depends on the color. Will every red LED have the same voltage drop? No, because production variations will mean that the wavelength (color) will not be the same, and thus the voltage drop will have differences. The peak wavelength has typically a ±10% variation.

If there are temperature differences between two LEDs, this will give a color change and hence differences in voltage drop. As the temperature rises, it is easier for electrons to cross the energy barrier. Thus the voltage drop reduces by approximately 2 mV per degree as the temperature rises.

Since the semiconductor material is not a perfect conductor, some resistance is in series with this constant voltage load, see Figure 2.4. This means that the voltage drop will increase with current. The ESR (equivalent series resistance) of a low power 20 mA LED is about 20 ohms, but a 1 W 350 mA LED has an ESR of about 1–2 ohm (depending on the semiconductor material used). The ESR is roughly inversely proportional to the current rating of the LED. The ESR will have production variations too.

The ESR can be calculated by measuring the increase in forward voltage drop divided by the increase in current. For example, if the forward voltage drop increases by from 3.5 V to 3.55 V (a 50 mV increase) when the forward current goes from 10 mA to 20 mA (a 10 mA increase), the ESR will be 50 mV/10 mA = 5 ohms.

In Figure 2.4, the Zener diode is shown as a perfect device. In reality, Zener diodes also have ESR, which can be higher than the ESR of an LED. For initial testing of an LED driver, a 5 W, 3.9 V Zener diode can be used to replace the (white) LED. If the

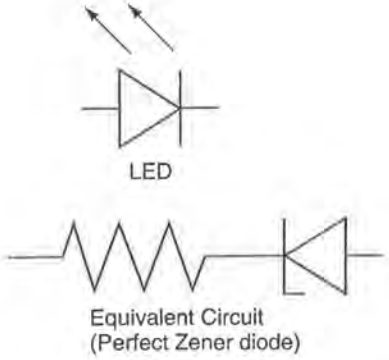

Figure 2.4: Equivalent Circuit for an LED.

driver is not working as planned the Zener diode may be destroyed, but this is far less costly than destroying a power LED. Since the Zener diode does not emit light, the test engineer will not be dazzled.

2.4 Voltage Drop Versus Color and Current

The graph in Figure 2.5 shows how the forward voltage drop depends on the light color and on the LED current. At the point where conduction begins, the forward

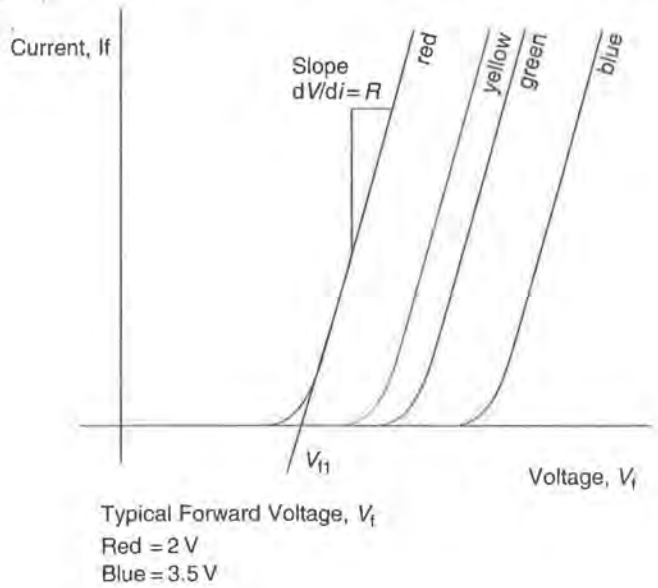

Figure 2.5: Forward Voltage Drop Versus Color and Current.

voltage drop, V_f, is about 2 V for a red LED and about 3.5 V for a blue LED. The exact voltage drop depends on the manufacturer, because of different dopant materials and wavelengths. The voltage drop at a particular current will also depend on initial V_f, but also on the ESR.

2.5 Common Mistakes

The most common mistake is to base a design on the typical forward voltage drop of the LED, $V_{f\,typ}$. This includes connecting strings of LEDs in parallel, with the assumption that the forward voltage drops are equal and the current will share equally between the two or more strings. In fact, the tolerance on the forward voltage drop is very high. For example, a 1 W white Luxeon Star has a typical $V_f = 3.42$ V, but the minimum voltage is 2.79 V and the maximum is 3.99 V. This is over ±15% tolerance on the forward voltage drop!

CHAPTER 3

Driving LEDs

3.1 Voltage Source

We have seen in Chapter 2 that an LED behaves like a constant voltage load with low equivalent series resistance (ESR). This behavior is like a Zener diode – in fact Zener diodes make a good test load, rather than using expensive high power LEDs!

Driving a constant voltage load from a constant voltage supply is very difficult, because it is only the difference between the supply voltage and the load voltage that is dropped across the ESR. But the ESR is very low value, so the voltage drop will also be low. A slight variation in the supply voltage, or the load voltage, will cause a very large change in current; see curve A in Figure 3.1.

If the variation in supply voltage and forward knee voltage (V_f) is known, the variation is current can be calculated. Remember that there are variations in LED

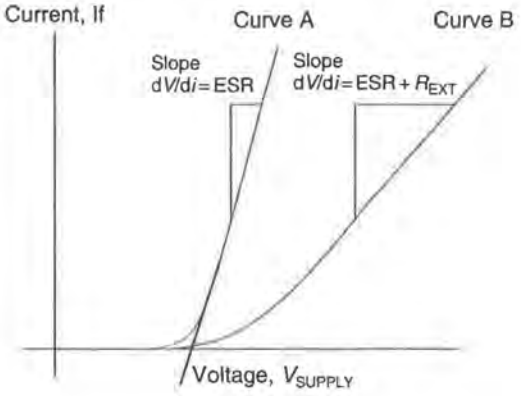

Figure 3.1: LED Current Versus Supply Voltage.

voltage drop due to manufacturing tolerances and operating temperature. Most supply voltages from a regulated supply have a 5% tolerance, but from unregulated supplies like automotive power, the tolerance is far greater.

$$I_{MIN} = \frac{V_{SOURCE\_MIN} - V_{F\_MAX}}{ESR}$$

$$I_{MAX} = \frac{V_{SOURCE\_MAX} - V_{F\_MIN}}{ESR}$$

These equations assume that ESR is constant. In practice, the V_f and voltage drop across ESR are combined, since manufacturers quote the voltage drop at a certain forward current. The actual V_f can be determined from graphs, or measured.

If there is a large difference between the source and load voltage, and a high ESR, there is very little difference between the maximum and minimum LED current. This may be perfectly adequate for low current LEDs, up to 50 mA. However, in high power LED circuits, a large voltage drop across a series resistor will be inefficient and may cause heat dissipation problems. Also, the ESR of LEDs is lower as the power rating increases. A standard 20 mA LED may have an ESR of 20 ohms, but a 350 mA LED will have an ESR of 1–2 ohms typically. Thus a 1 V difference in supply voltage could increase the LED current by 1 A in a power LED. Even in low current LEDs, the proportional change in current can be high.

3.1.1 Passive Current Control

Although the LED voltage drop shifts the curve of the graph to the right, the slope of the graph is just due to the ESR. Low current loads can have a relatively high value resistance added in series, in order to reduce the slope of the current versus voltage graph; see curve B in Figure 3.1.

With a series resistor added we are able to calculate the variation in current, provided that the variation in supply voltage and load voltage is known. In the equations below, the load voltage includes the voltage drop across ESR, at the rated current, so only the external resistor value is needed.

$$I_{MIN} = \frac{V_{SOURCE\_MIN} - V_{LOAD\_MAX}}{R_{EXT}}$$

$$I_{MAX} = \frac{V_{SOURCE\_MAX} - V_{LOAD\_MIN}}{R_{EXT}}$$

As an example, let us drive from an automotive supply; this is a nominal 13.5 V, but for this exercise we can set the limits at 12 V to 16 V. Let us select a red LED for tail-lights (Lumileds Superflux HPWA-DDOO), with a forward voltage drop of 2.19 V to 3.03 V at 70 mA forward current. Choosing to connect two LEDs in series, with a series resistor, we have a typical voltage drop of 5 V. So the typical voltage drop at 70 mA needs to be 8.5 V; this means that the series resistor should be 121.43 ohms. The nearest standard value resistor is 120 ohms, rated at 1 W since we will have a typical power dissipation of 588 mW.

$$I_{MIN} = \frac{V_{SOURCE\_MIN} - V_{LOAD\_MAX}}{R_{EXT}} = \frac{12 - 6.06}{120} = 49.5\,\text{mA}$$

$$I_{MAX} = \frac{V_{SOURCE\_MAX} - V_{LOAD\_MIN}}{R_{EXT}} = \frac{16 - 4.38}{120} = 96.83\,\text{mA}$$

At the high limit of source voltage, the LED is overdriven by 38%. But there is almost a 2:1 ratio between I_{MAX} and I_{MIN}, so if we increase R by 38% the worst case current levels are 70 mA maximum, but only 35.78 mA minimum.

In the previous calculations, the voltage drop across ESR (0.672 V) was included in the minimum and maximum load voltage values, so we ignored ESR. From the manufacturer's data sheet of the Lumileds HPWA-DDOO LED, graphs show that the ESR is about 9.6 ohms. Suppose we now want to operate at a lower current. Using the same example, but operating with a typical LED current of 50 mA, we must modify the results. Now the voltage at the current knee is $V_f = 1.518$ V to 2.358 V. With a typical 13.5 V supply and 50 mA, the value for V_f is 1.828 V. The total resistance needed is 196.88 ohms, but we already have 9.6 ohms ESR. An external resistor value of 180 ohms is the nearest preferred value for a current of 50 mA.

$$I_{MIN} = \frac{V_{SOURCE\_MIN} - V_{LOAD\_MAX}}{ESR + R_{EXT}} = \frac{12 - 4.716}{189.6} = 38.42\,\text{mA}$$

$$I_{MAX} = \frac{V_{SOURCE\_MAX} - V_{LOAD\_MIN}}{ESR + R_{EXT}} = \frac{16 - 3.036}{29.6} = 61.85\,\text{mA}$$

The series resistor has a higher value, so the variation in current is reduced to 1.6:1 ratio. The maximum current is now below the LED current rating of 70 mA.

Unless the LEDs are matched (or 'binned') to ensure the same forward voltage drop, the current through one string could be considerably different from the current through another.

When multiple LEDs are used to provide lighting for an application, they are frequently connected in an array, consisting of parallel strings of series connected LEDs. Since the LED strings are in parallel, the voltage source for all strings is the same. However, due to variations in forward voltage for each LED, the total voltage drop of each string differs from the other strings in the array. The forward voltage also depends on the ambient temperature. To ensure uniform light output for all LEDs, equal current should be designed to flow through each string of LEDs.

The traditional way is to connect a current limiting resistor in series with each string and power all the strings using a single voltage source. A substantial voltage needs to be dropped across the resistor to ensure that the current will stay in the desired range in the presence of temperature and device-to-device voltage variations. This method is inexpensive, but suffers from power inefficiency and heat dissipation. It also requires a stable voltage source.

A better way of powering the LED array is to regulate the total current through all the strings and devise a means to divide that total current equally among the LED strings. This is active current control and is the subject of the next subsection.

3.1.2 Active Current Control

Since a series resistor is not a good current control method, especially when the supply voltage has a wide tolerance, we will now look at active current control. Active current control uses transistors and feedback to regulate the current. Here we will only consider limiting LED current when the energy is supplied from a voltage source; driving LEDs using energy from current sources will be discussed in Section 3.2.

A current limiter has certain functional elements: a regulating device such as a MOSFET or bipolar transistor; a current sensor such as a low value resistor; and some feedback (with or without gain) from the current sensor to the regulating device. Figure 3.2 shows these functions.

The simplest current limiter is a depletion mode MOSFET; it has three terminals called gate, drain and source. Conduction of the drain-source channel is controlled from the gate-source voltage, like any other MOSFET. However, unlike an enhancement MOSFET, a depletion mode MOSFET is 'normally-on' so current flows when the gate-source voltage is zero. As the gate voltage becomes negative with respect to the source, the device turns off, see Figure 3.3. A typical pinch-off voltage is –2.5 V.

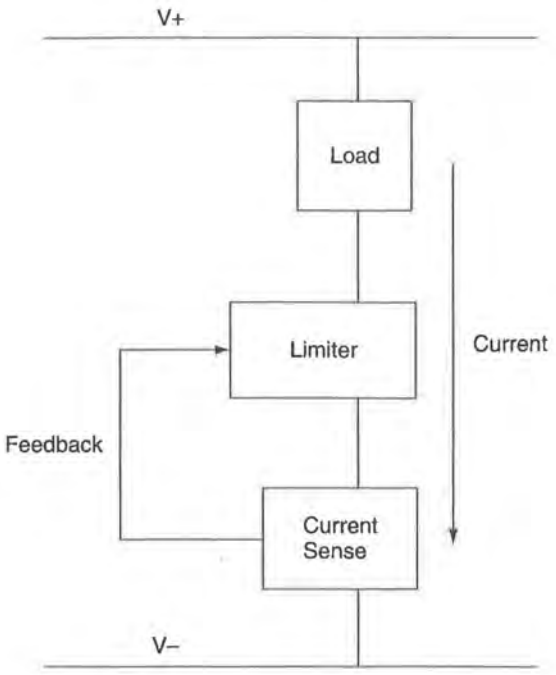

Figure 3.2: Current Limiter Functions.

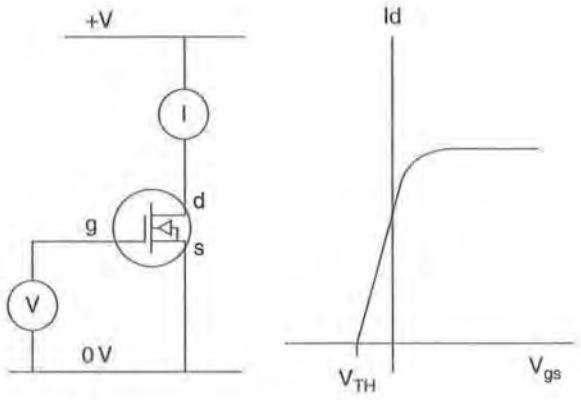

Figure 3.3: Depletion MOSFET Characteristics.

A current limiting circuit with a depletion mode MOSFET uses a resistor in series with the source to sense the current (see Figure 3.4). The gate is connected to the negative supply (0 V). As current flows through the resistor, the voltage drop across it

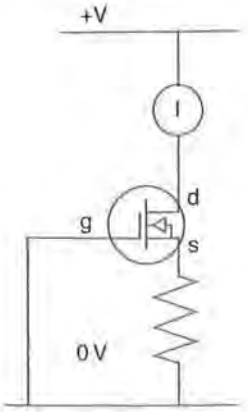

Figure 3.4: Depletion MOSFET Current Limiter.

increases. The voltage at the MOSFET source increases in potential compared to the 0 V rail and the MOSFET gate. In other words, compared to the MOSFET source, the gate becomes more negative. At a certain point, when the voltage drop approaches the MOSFET pinch-off voltage, the MOSFET will tend to turn off and thus regulate the current.

The main drawback of using depletion-mode MOSFETs is that the gate threshold voltage (V_{th}) has a wide tolerance. A device with a typical V_{th} of –2.5 V will have threshold range of –1.5 V to –3.5 V. However, the advantage is that high drain-source breakdown voltages are possible and so a limiter designed using a depletion-mode MOSFET can protect against short transients (longer periods of high voltage would tend to overheat the MOSFET).

A simple integrated current limiter is a voltage regulator in the place of the depletion-mode MOSFET, as shown in Figure 3.5. This uses an internal voltage reference and so tends to be quite accurate. The disadvantage is that there is a minimum dropout voltage of about 3 V. This circuit can be used for current sink or current source regulation, depending on whether the load is connected to the positive or negative supply rail.

The LM317 has a feedback pin called 'REF', and this controls the regulation of the current. When the voltage drop across the resistor tries to exceed 1.25 V, the current through the LM317 is reduced until the output terminal (OUT) is reduced below 1.25 V.

If accurate current limiters are used, parallel strings of LEDs can be connected to the same voltage source and then each string will have approximately the same current.

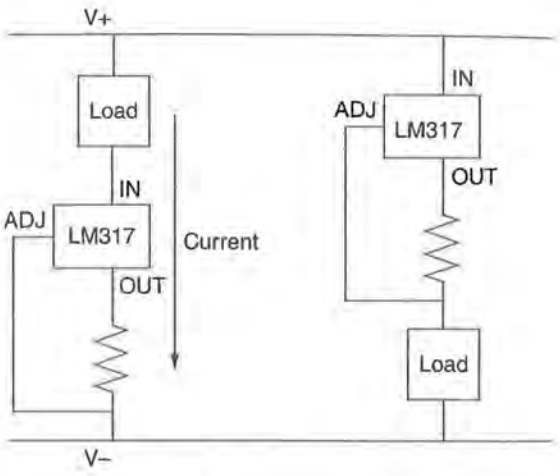

Figure 3.5: Linear Regulator as Current Limiter.

With the same current flowing through each LED, the light produced will be almost the same for each LED and thus no 'bright spots' will be seen in the LED array.

The current limiters described here are purely to show how LEDs can be driven from a constant voltage supply. Further linear regulators are described in Chapter 4. Switching regulators are described in Chapters 5–10.

3.1.3 Short Circuit Protection

The current limiting circuits described in the previous subsection will provide automatic short circuit protection. If the LED goes short circuit, a higher voltage will be placed across the current limiter. Power dissipation is the main issue that needs to be addressed.

If the power dissipation cannot be tolerated when the load goes short circuit, a voltage monitoring circuit will be needed. When a higher than expected voltage is placed across the current limiter, the current must be reduced to protect the circuit. In the LM317 circuit previously described, the regulator itself has thermal shutdown.

3.1.4 Detecting Failures

If we have a short circuit condition in the LEDs, the voltage across the current limiter will increase. We can use this change to detect a failure. In the circuit shown in

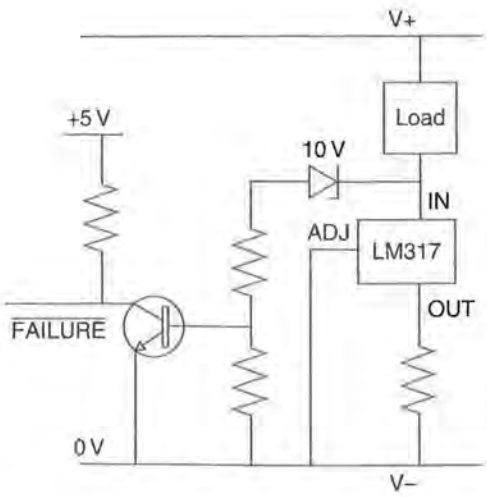

Figure 3.6: Shorted Load Indication.

Figure 3.6, a 10 V Zener diode is used in series with the base of an NPN transistor. When the voltage at the 'IN' terminal of the LM317 reaches about 11 V, the Zener diode conducts and turns on the transistor. This pulls the 'FAILURE' line to 0 V and indicates a short circuit across the LEDs.

3.2 Current Source

Since an LED behaves like a constant voltage load, it can be directly connected to a current source. The voltage across the LED, or string of LEDs, will be determined by the characteristics of the LEDs used. A pure current source will not limit the voltage, so care must be taken to provide some limit; this will be covered in more detail in the next subsection.

If the current source produces much more current than the LED requires, current-sharing circuits will be required. The simplest of these is a current mirror, which shares the current equally between strings based on the current flowing through the primary string.

Figure 3.7 shows a simple current mirror. The basic principle relies on the fact that matched transistors will have the same collector current if their base-emitter junctions have the same voltage across them. By connecting all the bases and all the emitters

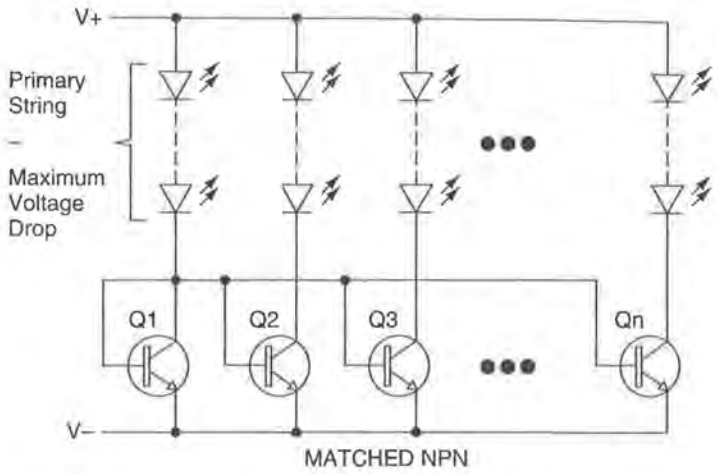

Figure 3.7: Current Mirror.

together, every base-emitter junction voltage must be equal and therefore every collector current must be equal.

The primary LED string is the one that controls the current through the other strings. Since the collector and base of transistor Q_1 are connected, the transistor will be fully conducting until the collector voltage falls low enough for the base-emitter current to limit. Other transistors (Q_2 to Q_n) have their base connections joined to Q_1, and will conduct exactly the same collector current as Q_1 since the transistors are matched. The total current through Q_1 to Q_n will equal the current source limit.

The voltage drop across the LEDs in the primary string must be higher than any other string in order for the current mirror to work correctly. In the slave strings, some voltage will be dropped across the collector-emitter junction of the transistors Q_2-Q_n. The slave circuits adjust the current by raising or lowering this surplus voltage drop across the transistor.

3.2.1 Self-Adjusting Current Sharing Circuit

As an alternative, the current sharing circuit shown in Figure 3.8 automatically adjusts for string voltage.

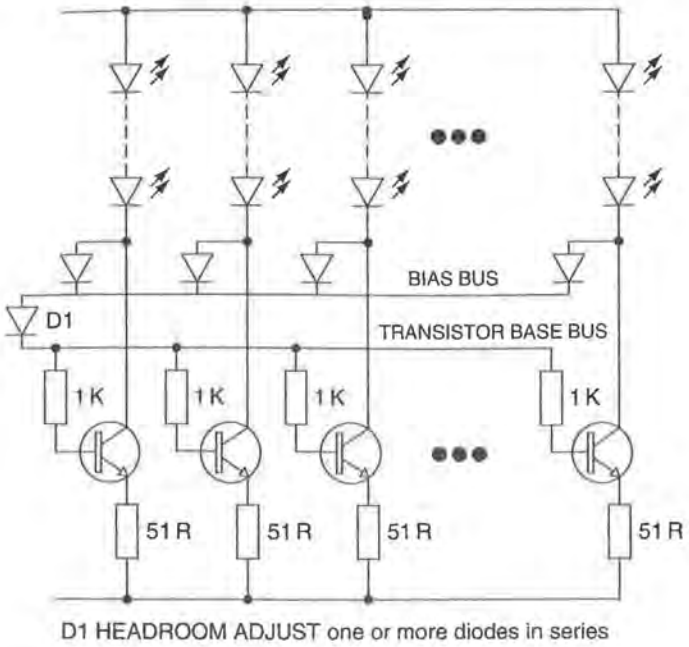

Figure 3.8: Self-Adjusting Current Sharing Circuit.

Assuming that the LED array is driven from a current source, there will be equal current division among all connected branches. If any branch is open due to either a failure or no connection by design, the total current will divide evenly among the connected branches. Unlike the simple current mirror, this one automatically adjusts for the maximum expected voltage difference between strings of LEDs, which is a function of the number of LEDs in the string and the type of LED used. The components must be able to dissipate the heat generated by the sum of each string current and the headroom voltage drop across the regulator for that string.

In high reliability applications, the failure of a single LED should not materially affect the total light output. The use of the current divider will help the situation. When an LED fails short, the voltage of the string containing the shorted LED will have less voltage. The current divider will accommodate the change in voltage and still distribute the current equally. When the failed LED string opens, the current divider will automatically redistribute the total current among the remaining strings, thus maintaining the light output. In this application, an extra diode string can be added for redundancy, so that any single failure will not cause the remaining LEDs to operate in an over-current condition.

Equality of current division among the branches is dependent on the close matching of the transistors, which are in close vicinity (ideally a single package with several matched transistors). When any of the transistors saturate due to large variation of the string voltages, equal current division will be lost.

Diodes connected to each collector detect the voltage of each branch. The highest branch voltage (corresponding to the LED string with the lowest forward voltage) is used to bias the transistors in the linear operating region. The cathode of each diode is connected to a common 'bias bus'.

To accommodate variations in string voltages and keep the current divider transistors from saturation, diodes are connected between the 'bias bus' and the 'transistor base bus'. More than one external diode can be used to accommodate large voltage variations. If the string voltage variation is less than one diode drop, the two buses can be joined.

When a branch is not connected, there will be higher base current flowing in the associated regulating transistor. This could interfere with the current division in the connected branches, so a resistor (about 1 kohm) is connected from the 'transistor base bus' to each transistor base to ensure correct operation of the overall circuit.

3.2.2 Voltage Limiting

In theory, the output voltage of a constant current driver is not limited. The voltage will be the product of the current and load resistance in the case of a linear load. In the case of an LED load, the voltage limit will depend on the number of LEDs in a string.

In practice, there will be a maximum output voltage, because components in the current source will break down eventually. Limiting the LED string voltage is necessary to prevent circuit damage and the voltage level will depend on the particular circuit.

Safety regulations will be covered in Chapter 10, but Underwriters Laboratories (UL) Class 2 and Safety Electrical Low Voltage (SELV) requirements limit any potential to 60 V DC, or 42.4 V AC, so equipment designed to meet these requirements should consider both mains supply isolation (if applicable) and output voltage limiting. The number of LEDs in a string will be restricted in this case, so that the total string voltage remains below 60 V.

3.2.3 Open Circuit Protection

Some constant current drivers, especially switching boost converters, will produce a sufficiently high voltage to destroy the driver circuit. For these types of driver a shutdown mechanism is required. Using a Zener diode to give feedback when the output voltage exceeds a certain limit is the standard method. Some over-voltage detectors within integrated circuits (ICs) have a latched output, requiring the power supply to be turned off and then on again before LED driver functions are enabled. Other circuits will auto-restart when the open circuit condition is removed (i.e. when the LEDs are reconnected).

Some ICs have an over-voltage detector (internal comparator) that disables the LED driver circuit when the voltage at the input exceeds the reference voltage. A potential divider comprising two resistors is usually used to scale down the output voltage to the reference voltage level.

3.2.4 Detecting LED Failures

In a constant current circuit, a failure of an LED can mean that either a whole string is off (open circuit LED) or a single LED is off (short circuit LED).

In the case of an open circuit LED, the load is removed and so the output voltage from the current source rises. This rise in voltage can be detected and used to signal a failure. In circuits where over-voltage protection is fitted, this can be used to indicate a failure.

If a current mirror is used to drive an array of LEDs with a number of strings, the result of an open circuit LED will depend on which string the LED is located. In a basic current mirror, as shown in Figure 3.7, a failure in the primary string will cause all the LEDs to have no current flow and not be lit. Detection of the rise in output voltage would be a solution. However, if the failure were in a secondary string, there would be higher current flowing in the other strings and the output voltage would not rise very much (only due to the extra current flowing through the ESR). The voltage at the transistor collector of the broken string would fall to zero since there is no connection to the positive supply, and this could be detected.

Another technique, for low current LEDs, is to connect the LED of an opto-coupler in series with the LED string. A basic opto-coupler has an LED and a photo-transistor in the same package. Current through the opto-coupler LED causes the photo-transistor to conduct. Thus when current is flowing through the LED string

and the opto-coupler's internal LED, the photo-transistor is conducting. If the string goes open-circuit, there is no current through the opto-coupler's LED and the photo-transistor does not conduct.

3.3 Testing LED Drivers

Although testing an LED driver with the actual LED load is necessary, it is wise to use a dummy load first. There are two main reasons for this: (1) cost of an LED, especially high power devices, can be greater than the driver circuit; and (2) operating high brightness LEDs for a long time under test conditions can cause eye strain and temporary sight impairment (if LEDs viewed at close range). A further reason is that some dummy loads can be set to limit the current and so enable fault-finding to be made easier.

3.3.1 Zener Diodes as a Dummy Load

Figure 3.9 shows how Zener diodes can be used as a dummy load. This is the simplest and cheapest load. The 1N5334B is a 3.6 V, 5 W Zener diode (3.6 V typical at 350 mA). This is not the perfect dummy load. This reverse voltage is slightly higher than the typical forward voltage of 3.42 V of a Lumileds 'Luxeon Star' 1 W LED. The 1N5334B has a dynamic impedance of 2.5 ohms, which is higher than the Luxeon Star's 1 ohm impedance. The impedance will have an effect on some switching LED drivers that have a feedback loop. For simple buck circuits, the impedance only has a small effect.

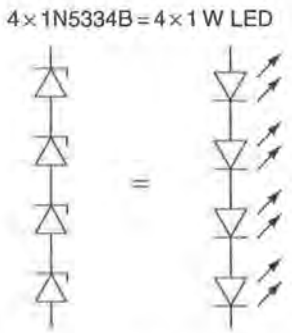

Figure 3.9: Zener Diode Dummy Load.

An active load is more precise. A constant voltage load will have (in theory at least) zero impedance, so simply adding a small value series resistor will give the correct

impedance. Commercial active loads can be set to have constant current or constant voltage – a constant voltage setting is required to simulate an LED load.

A constant voltage load built using a low cost discrete solution is shown in Figure 3.10. This is a self-powered load and so can be isolated from ground. The Zener diode can be selected to give the desired voltage (add 0.7 V for the emitter-base junction of the transistor). The transistor should be a power device, mounted on a heatsink.

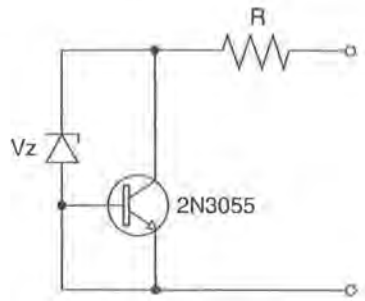

Figure 3.10: Active Dummy Load.

The circuit is Figure 3.10 has low impedance. Although the Zener diode does have a few ohms impedance, the current through it is very small and the effect of the transistor is to reduce the impedance by a factor equal to the gain HFE. Suppose the transistor HFE = 50 at 1 A and the Zener diode impedance $Z_d = 3$ ohms. Changing the collector current from 500 mA to 1 A will cause the base current to rise from 10 mA to 20 mA. A 10 mA change in current through the Zener diode will cause 30 mV voltage rise. This change at the transistor collector is equivalent to an impedance of 30 mV/0.5 A = 0.06 ohm. In other words, the circuit impedance is equal to the Zener diode impedance divided by the transistor gain.

An impedance of 0.06 ohm is unrealistically low, but a power resistor can be added in series to give the desired load impedance. Because of the potentially high load current, both the transistor and series resistor should be rated for high power. The transistor should be mounted on a large heatsink.

3.4 Common Mistakes

The most common mistake is to use expensive high power LEDs when testing a prototype circuit. Instead, 3.6 V, 5 W Zener diodes should be used in place of each LED. Only once the circuit has been tested under all conditions should LEDs be used.

3.5 Conclusions

A voltage regulated LED driver is preferred when there are a number of LED modules that can be connected in parallel. Each module will have its own linear current regulator. An example would be channel lighting, as used in shop name boards.

A current regulated LED driver is preferred when it is desirable to have a number of LEDs connected in series. A series connection ensures that all the LEDs have the same current flowing through them and the light output will be approximately equal.

A switching driver with constant current output is the favored option when driving high power LEDs, for reasons of efficiency. An efficiency of 75–90% can be achieved. If a constant voltage source were used, the LEDs would also need a high current linear regulator in series, which is very inefficient and would increase heat dissipation problems.

CHAPTER 4

Linear Power Supplies

4.1 Introduction

Linear power supplies for driving LEDs are preferred for a number of reasons. The complete absence of any EMI radiation is one important technical reason. Lowest cost is an important commercial reason. However, they also have disadvantages: in some applications they have low efficiency and hence the introduction of thermal problems; in other applications, such as when powered from the AC mains supply, they have the disadvantage of large size.

4.1.1 Voltage Regulators

Many voltage regulators are based on the LM317 originally from National Semiconductor, but which is now made by a number of manufacturers. Inside the LM317 are: (1) a power switch, which is an NPN transistor; (2) a voltage reference set to produce 1.25 V and (3) an operational amplifier (op-amp) to control the power switch, as shown in Figure 4.1. The op-amp tries to keep the voltage at the output equal to the voltage at the adjust (ADJ) pin minus the reference voltage.

To produce a certain output voltage, a feedback resistor is connected from the output (OUT) to the ADJ pin and a sink resistor is connected from the ADJ pin to ground, thus creating a potential divider. Usually the feedback resistor is set to 240 ohms, in order to draw a minimum of 5 mA from the regulator and help to maintain stability.

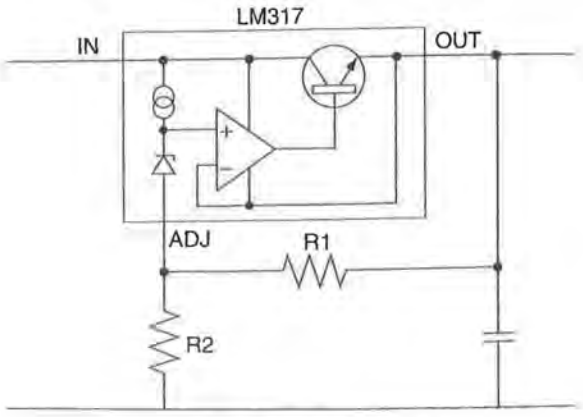

Figure 4.1: LM317 Regulator.

A capacitor on the output terminal also helps with stability. The output voltage is given by the equation:

$$V_{OUT} = 1.25 * \frac{1 + R2}{R1} + I_{ADJ} * R2$$

Note, $I_{ADJ} = 100\,\mu A$, worst case.

Variations of the LM317 regulator include fixed positive voltage versions (LM78xx) and negative voltage versions (LM79xx), where 'xx' indicates the voltage; i.e. LM7805 is a +5 V 1 A regulator.

The LM317 and its variants need a minimum input to output voltage difference to operate correctly. This is typically in the range 1 V to 3 V, depending on the current through the regulator (higher current requires a higher voltage differential). This input to output voltage difference is equal to the voltage across the internal constant current generator, since the OUT pin is at the same potential as the voltage reference.

Low dropout voltage regulators use a PNP transistor as the power switch, with the emitter connected to the IN terminal and the collector connected to the OUT terminal, see Figure 4.2. They also have a ground pin that enables an internal reference voltage to be generated independent of the input to output voltage differential. A dropout voltage of less than 1 V is possible.

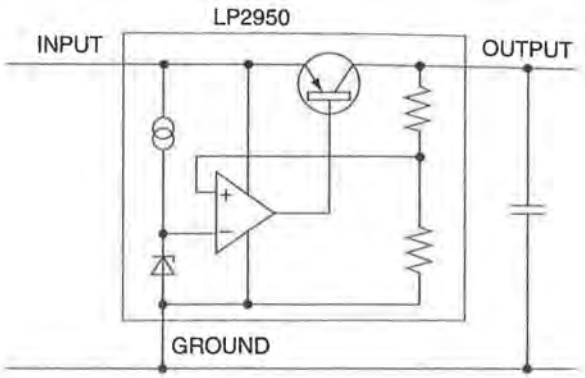

Figure 4.2: Low Dropout Voltage Regulator.

4.1.2 Voltage Regulators as Current Source or Sink

In Figure 4.3 are shown two circuits using a voltage regulator as a current limiter, one is configured as a current source and the other as a current sink.

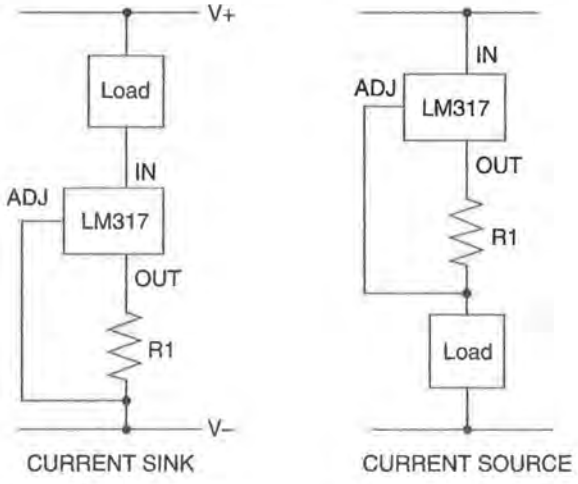

Figure 4.3: Constant Current Circuits Using the LM317.

As previously described, the LM317 regulates when there is +1.25 V between the OUT and ADJ pins. In Figure 4.3, a current sense resistor ($R1$) is connected between the OUT and ADJ pins. Current flowing through $R1$ will produce a voltage drop, with the

OUT pin becoming more positive than the ADJ pin. When the voltage drop across $R1$ reaches 1.25 V, the LM317 will regulate the current. Thus the current limit is

$$I = \frac{1.25}{R1}$$

4.1.3 Constant Current Circuits

There are many constant current circuits; some using integrated circuits, some using discrete components, and others using a combination of both ICs and discrete devices. In this subsection, we will examine some examples of each type.

A simple constant current sink uses an op-amp with an input voltage range that extends to the negative rail, as shown in Figure 4.4. In order to set the current level, a voltage reference is required. The voltage drop across a current sensing resistor is compared to the reference voltage and the op-amp output voltage rises or falls to control the current. The voltage reference can be a temperature compensated precision reference, or a Zener diode. A Zener diode generally has a smallest temperature coefficient and lowest dynamic impedance at a breakdown voltage of 6.2 V.

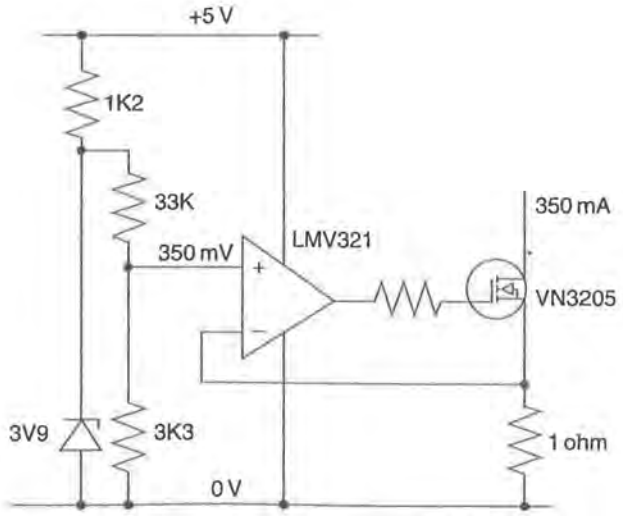

Figure 4.4: Constant Current Sink Using Op-amp.

4.2 Advantages and Disadvantages

The advantage of linear power supplies is that they produce no EMI radiation. This advantage cannot be overstated.

A switching power supply may appear to have few components, but this does not take into account the EMI filtering and screening. These additional circuits can double the overall cost of the LED driver. If the LEDs are distributed, such as in channel lighting where there is no opportunity to shield any EMI, both common mode and differential filtering are required. And common mode chokes are expensive!

One disadvantage of a linear LED driver can be low efficiency, which is the ratio of the LED voltage to the supply voltage. The efficiency is low only if the supply voltage is somewhat higher than the LED voltage. In these cases, poor inefficiency causes the introduction of thermal problems. A heatsink may be required, which is bulky and moderately expensive. It should be noted that where the supply voltage is only a little higher than the LED voltage, the efficiency of a circuit using linear regulator could be higher than one using a switching regulator.

Linear mains powered LED drivers have the disadvantage of large size, because a step-down transformer is almost always required (unless the LED string voltage is very near to the peak AC supply voltage). A 50 Hz or 60 Hz mains transformer is bulky and heavy. Smoothing capacitors after the bridge rectifier are also very bulky. The efficiency will vary as the AC supply voltage rises and falls over a long period, because the difference between the rectified voltage and the LED string voltage will change.

4.3 Limitations

The main limitation of a linear supply is that the LED voltage will always be lower than the supply voltage. Linear voltage and current sources cannot boost the output voltage so that the output is higher than the input. Where the output voltage could be higher than the input voltage a switching regulator is necessary. These will be discussed in the next few chapters.

4.4 Common Errors in Designing Linear LED Drivers

The most common error is to ignore the power dissipation. Power dissipation is simply the voltage drop across the regulator multiplied by the current through it.

If the voltage drop is high, the current must be limited to stay within the device package power dissipation limits. A surface mount D-PAK package may be limited to about 1 W, even when there is some copper area soldered to the tab terminal. Heatsinks are now available for surface mount packages, which eases the problem.

Another error is to ignore the start-up conditions. The voltage rating of the regulator must be high enough to allow for the output being connected to 0 V (ground). This is because at start-up, the output capacitor will be uncharged and thus at 0 V. Only after operating for a short period does the output capacitor charge, which reduces the voltage drop across the regulator. The voltage rating of the regulator should always be greater than the maximum input voltage expected.