Power Supply Design for LED Flashlights
By Henry Schneiker
September 2007

Designing the most efficient power supply for a high power white LED is more difficult that you may think. The task gets more difficult if you wish to support several discrete brightness settings and minimize color shift at lower power settings. And the task get even more difficult if your power source overlaps the LED voltage range.

For the purposes of this article we will skip any discussion of linear regulators as their range of application is fairly limited. We will also skip any discussion of charge pumps for the same reasons. However, it should be remembered that there are conditions where these other topologies can be the most efficient and/or the most optimum solution.

Converting Power

It is generally accepted that there are only three basic inductive switching power supply topologies: a) the boost converter, b) the buck converter and c) the buck-boost converter. These are illustrated in Figure 1. All other inductive switching power supply topologies are derived from these three basic topologies. The three referenced articles below provide a detailed analysis of the operation of these three topologies.

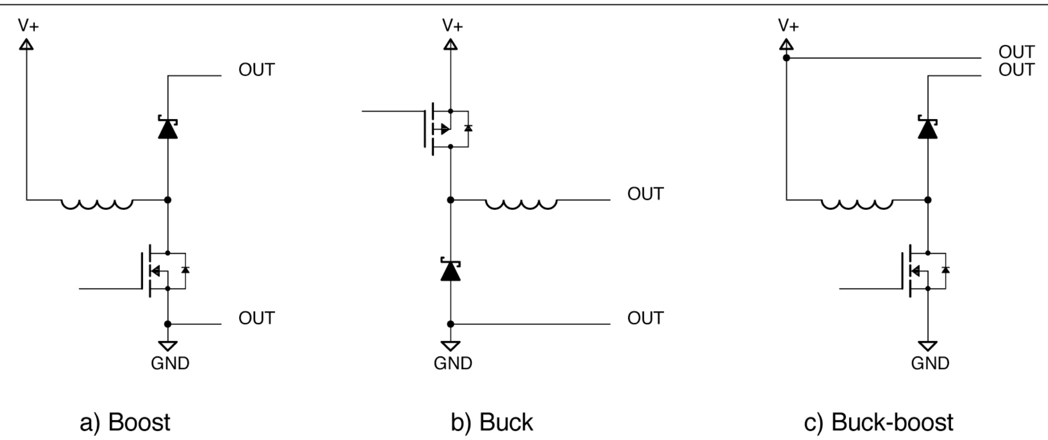

Figure 1: the three basic types of inductive switching topologies.

The diodes shown in Figure 1 can be replaced by or paralleled with a synchronous rectifier to increase efficiency. A synchronous rectifier is a switch that turns on when current is flowing in the forward direction to reduce or eliminate the forward voltage drop of the diode. Reducing the forward voltage drop of 0.4V to under 0.1V can have a significant positive impact on efficiency.

The buck and boost topologies have a theoretical efficiency advantage over the buck-boost topology because the power source and load are in series for one of the two phases of operation. This means that the inductor is never required to supply 100% of the power to the load. This results in lower peak currents and lower ripple. Conversely, the buck-boost topology has a theoretical efficiency disadvantage because the power source and load are never in series. This means that 100% of the power for the load must be provided by the inductor during one of the two phases. This results in higher peak currents and higher ripple.

If you connect the output of a buck converter to the input of a boost converter you end up with two inductors in series. If these two inductors are then combined into a single inductor the result is the buck-boost H-bridge topology. The buck-boost H-bridge topology is illustrated in Figure 2. Given the correct control signals the circuit can buck, boost or direct drive. The diodes can be replaced by or paralleled with synchronous rectifiers to increase efficiency.

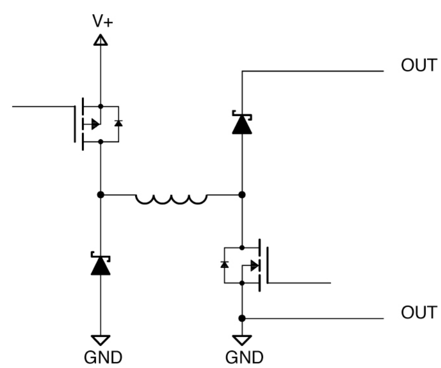

Figure 2: the buck-boost "H" bridge inductive switching topology.

It is clear from examining the circuit that one of the two upper arms of the H must always be on and the corresponding lower leg of the H must always be off. In the direct drive mode both upper arms are always on and both lower legs are always off.

The efficiency disadvantage of the H-bridge topology is that there are always two switches in series with the load. The design disadvantage of the H-bridge topology is the level of complexity required to make it work and to smoothly transition between buck and boost. However, this topology is still theoretically more efficient than the basic buck-boost topology because the power source and load are in series for one of the two phases and the resistance of the second switch can be made sufficiently small.

You can now purchase single chip controllers with on-board switches for each of the four topologies discussed. These chips can provide a big win if you can find one that conforms to your design. But you may also find that by the time you have added enough other parts to make one of these chips work, some other solution is more optimal - such as one based on a microprocessor.

A common element in all of these topologies is the inductor. Inductors come in all sizes and current ratings and are made from may different materials. A rule of thumb is that physically larger inductors are more efficient than physically smaller inductors. Inductor manufacturers rarely provide any information that can be used to determine how efficient an inductor will be other than the DCr (DC resistance) specification. Unfortunately, the resistive losses may be significantly lower that the core losses if an inductor is incorrectly chosen.

All three of the basic power supply topologies are characteristically voltage sources when operated in continuous mode. That is, if you connect a static load across the output, the current will change until the output voltage reaches the set value. If the static load changes, the current will change correspondingly until the output voltage again reaches the set value. The ratio between the input voltage and the output voltage is set by the duty cycle and the typology voltage transfer function. Therefore, if you know the input voltage and you know the desired output voltage you can calculate the exact duty cycle for each topology.

If the typology is operated in discontinuous mode the voltage transfer function changes and the voltage source characteristic is lost. The basic buck-boost topology changes from a voltage source in continuous mode to a constant power source in discontinuous mode.

Regulating Light Output

High power white LEDs have some interesting electrical characteristics that should be understood before selecting the power supply topology and the regulation method:

1) High power white LEDs have a low dynamic resistance typically in the range of 1 ohm.

2) The V-I curve changes dramatically from one LED to the next. The forward voltage covers a range of three quarters of a volt for a given current.

3) LEDs have a negative temperature coefficient in the range of -3mV/°C so the required voltage goes down as the LED heats up and should be compensated for to prevent thermal runaway at high power settings.

4) The efficiency of an LED goes down rapidly as the temperature goes up and can loose in the range of 20% efficiency by the time the junction temperature gets to 80°C.

5) The efficiency of an LED can vary over a range of 2:1 within the same bin so you may want to at least think about this when designing a flashlight.

There are three primary ways to regulate power to an LED: constant voltage, constant current and constant power.

Constant voltage regulation for an LED requires you to provide some method to set the power supply output voltage to match the V-I curve for the LED. Further, you should provide compensation for the LED's negative temperature coefficient at high power levels. Finally, you may want to compensate for the loss in efficiency as the LED warms up. Once these things have been done the LED output will remain constant.

Constant current regulation for an LED requires you to measure the current through the LED and then use that measurement to regulate the output voltage. Current is normally measured by passing the current through a resistor and measuring the resulting voltage but it can also be measured magnetically by measuring the magnetic field around one of the LED conductors. Constant current regulation automatically compensates for the V-I curve and the negative temperature coefficient but you may still want to compensate for the loss in efficiency as the LED warms up.

Finally, constant power regulation for an LED requires you to provide some method to set the power supply output power to match the V-I curve for the LED. Or you can measure the current and compensate the voltage to produce the same power. A unique feature of constant power regulation it that it automatically compensates for the loss in efficiency as the LED warms up - roughly.

Regulation methods that measure output circuit parameters to dynamically adjust the output are known as closed loop systems. Closed loop systems are fully automatic and typically do not require factory adjustments to make them work. This is good from a production standpoint because you just assemble the flashlight and ship it.

One disadvantage of a closed loop system is the potential complexity and added inefficiency of measuring the output circuit parameters. For instance, current is normally measured across a resistor. It should be obvious that a smaller value resistor will generate a smaller loss in the resistor. However, there is a trade-off with amplifying the signal from the resistor so it can be used by the controller. Smaller value resistors require more amplification and effectively raise noise. Current can also be measured by measuring the magnetic field. The magnetic sensor and conditioning electronics will consume power, add expense and take up real estate on the circuit board as well.

Another issue with a closed loop system is the delay between detecting the output condition and making changes that affect the output. If the controller is too fast or too slow the loop can become unstable or otherwise do a poor job of regulating.

Regulation methods that cannot measure output parameters are known as open loop systems because there is no feedback link between the output and the control system. Open loop regulation systems for LEDs must be calibrated at the factory to compensate for the V-I curve. The negative temperature coefficient is very consistent across all LEDs of the same model so the negative temperature coefficient compensation can be done algorithmically as part of a closed loop regulation system as long as temperature measurements are available. Some form of temperature calibration may be needed to improve the accuracy of the temperature sensor.

An open loop system depends on an accurate model using accurate parameters to produce accurate light output levels with the minimum of input signals. The input voltage and temperature may be the only measured parameters. Any other parameters are either measured at calibration time or hard coded into the model. The model then uses these parameters to calculate and generate the output signals and thus generate the desired output power to an acceptable accuracy.

One example of how this works is provided by the patent application referenced below. The model uses the inductor value and clock period to generate a known amount of energy per cycle from a known input voltage. The inductor value and the clock period are measured at calibration time and the input voltage is measured dynamically. The model knows the exact amount of power needed to produce the desired light output level. The power, light output and temperature are measured at calibration time. The model calculates how many energy cycles are needed per second to generate the required power and performs any additional temperature compensation desired.

Analog Versus Digital

We have seen that our power converters operating in continuous mode act as voltage sources. And we have also seen that the voltage transfer function for these voltage sources depend on the duty cycle. Therefore our ability to set the desired output voltage is determined by our ability to set the duty cycle.

In an analog converter the duty cycle can be arbitrarily long. In other words, there is no system preference on the length of a duty cycle within the valid range of duty cycles and thus the changes in duty cycle can be arbitrarily small. With arbitrarily small changes in duty cycle you can have arbitrarily small changes in output voltage.

The circuitry controlling the duty cycle in an analog converter is also analog and is susceptible to noise. This causes jitter in the duty cycle which in turn causes jitter in the output voltage. Analog converters use a closed loop regulation system to keep the output stable and to compensate for variations in the analog components.

In a digital converter the duty cycle has a resolution dependency determined by the controller's clock. The duty cycle has to be an integer number of clock cycles long and thus any difference between the desired duty cycle and the integer representation of the duty cycle generates an output voltage error. Depending on the clock's resolution, the converter's transfer function and the voltage ratio being represented, the error can be acceptably small or unacceptably large.

There are two different types of resolution errors that are important to us. The first is the absolute output error. As long as the absolute output changes slowly over time an absolute output error of 10% has very little visual affect - i.e., the user will never see the error. The second type of error is the inter-voltage error. This is the sudden change in output voltage for a very small change in input voltage. The inter-voltage error results in a sudden change in light output which is much easier for the eye to detect. The inter-voltage errors must be kept small and should result in less than a 5% change in light output to keep the user from noticing.

Conclusion

There are many ways to supply power to an LED. There are any number of marketing and engineering trade-offs when selecting the optimum power supply design. The simplest and least expensive solution that is consistent with your requirements will generally be the best solution. Change one seemingly trivial requirement and the optimum solution can be very different - so pick your requirements carefully.

References:

Understanding Buck Power Stages in Switchmode Power Supplies, March 1999, Texas Instruments Incorporated, application report SLVA057.

Understanding Boost Power Stages in Switchmode Power Supplies, March 1999, Texas Instruments Incorporated, application report SLVA061.

Understanding Buck-Boost Power Stages in Switch Mode Power Supplies, March 1999 - revised November 2002, Everett Rogers - Texas Instruments Incorporated, application report SLVA059A.

Regulate open-loop constant-power power supply, July 2005, Patent Application 20050151518.