Capacitor selection helps achieve long lifetimes for LED lights

Margery Conner - February 23, 2012

This presentation was originally given by Andrew Smith, product manager, LED Lighting at Power Integrations for EDN’s May 2011 live LED event in San Jose.

Consumers often see LED lamp failures. If you look at the growing number traffic lights using LEDs, for example, you might see that many individual LED segments are no longer working. Early deployments, such as LED street lights in Asia, have experienced many failures. An examination of these failures shows that the LEDs themselves have not failed; rather, the power supplies that provide the power to the LED circuit have failed. We need to understand why LED lamps are failing and what it is about the power supply that is limiting the lifetime of the deployed circuits so that we can develop a better solution to improve LED lamp lifetimes.

One major issue is that LED lighting environments are very stressful for the power supply. LED lamps will typically run at full load for their entire operating period and they operated in an extremely high ambient environment.

An LED lamp will generate a large amount of heat, like any other lighting circuit (about 80% of the output from the power supply is lost as heat). The problem is that the LED lamp is located very close to the power supply. Therefore, the power supply itself sees the equivalent of its full rated output power (its own dissipation plus 80% of the output power) being dissipated as heat in its proximity.

With that introduction, let’s begin by looking at what causes LED power supplies to fail. There are two basic causes: heat and time. As the temperature rises, the likelihood of LED lamp failure increases and, as we have noted, high temperatures (often in excess of 90°C) are the norm for LED lamps.

When we examine the effect of heat, we find that the optocouplers and aluminum electrolytic capacitors are the most vulnerable components in the power supply. We are not going to cover the optocouplers today since that subject would comprise an entire paper. We are going to concentrate on what happens to an electrolytic capacitor in the circuit, how heat affects it over time, and what happens when the electrolytic capacitor gets to the end of its life. We will then look at how to fix the problem by removing electrolytic capacitors from key circuit locations.

First, let’s talk about the lifetime of an LED lamp. ENERGY STAR is specifying a lifetime requirement of more than 25,000 hours for residential applications and more than 35,000 hours for commercial applications. They describe the L70* characteristic for the lamp. This means that the relative light output must not fall below 70% of its initial brightness value in less than the rated lifetime of the system. (Lumen depreciation is the decrease in lumen output that occurs. L70 means that lumen depreciation to 70% of initial lumen output; stated conversely, it indicates 70% lumen
Lifetime of the circuit is only as long as that of the element in the circuit with the shortest lifetime. As seen in Fig. 1, the typical high-brightness LED circuit could last perhaps 45,000 hours before it will get to the L70 point. However, lifetime for a typical power supply may be only 20,000 hours. So what effectively happens is that it doesn't really matter how strong your LED is if the power supply behind it can only last 20,000 hours.

Wasting the lifetime of these LEDs is not a good thing. Fig. 2 shows lifetime in hours along the bottom and failure rate on the vertical axis. (We haven't actually populated the vertical axis because the numbers don't really matter for this discussion.)
The dark blue line is the lifetime expected for the power supply, and the brown line shows the lifetime expected for the LEDs. You can see that the LEDs last significantly beyond the blue line, which represents the point at which the power supply begins to fail. The red area beneath the blue curved area represents early failure of the power supply. That is the wasted life which the LEDs still possess at the end of the system’s operation.

Think of it this way: If you bought a car with drive chain that lasts one million miles, but the wheels fall off at 50,000 miles, you’ve paid for a drive train that you’re never going to get full use of. Similarly, the power supply is dying very early. While the LEDs are still good for a long time, the lamp life has reached an end and you throw it away because the power supply failed. Moreover, if we’re using an inadequate standard power system design, the rising temperature of the power supply will also dramatically reduce the power supply’s life, making it even worse than shown here.

So what’s the source of the power supply’s lifetime problem? I already suggested that the main culprits are the aluminum electrolytic capacitors. But first, let’s take a look the rated lifetimes of the other components.

If we look at an LED string, based on L70, you can get to 45,000 hours quite easily. Fig. 3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Rated Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Based on L70</td>
<td>45,000 hours</td>
</tr>
<tr>
<td>Controller</td>
<td>&gt;&gt;3 100,000 hours</td>
</tr>
<tr>
<td>Other Semiconductors</td>
<td>&gt;&gt; 100,000 hours</td>
</tr>
<tr>
<td>Electrolytic Capacitors</td>
<td>~20,000 hours (~3 year)</td>
</tr>
<tr>
<td>Ceramic Capacitors</td>
<td>Not defined by manufacturers</td>
</tr>
</tbody>
</table>

- The controllers last longer much longer than 100,000 hours, so they don’t wear out very quickly.
- The other semiconductors have lifetimes that exceed 100,000 hours.
- Diodes and transistors really last a long time. These components don’t have a lifetime problem.
- Ceramic capacitors last a very long time and are not a concern.
Aluminum electrolytic capacitors, however, have a short life expectancy of perhaps 20,000 hours, which largely determines the LED system lifetime since this translates into only about one year of operation.

The structure of the aluminum electrolytic capacitors, subjected to a high ambient temperature, shortens the life of the power supply.

**Fig. 4** shows a typical two-stage LED driver, commonly seen in applications today. This is a standard power supply that has to face the harsh temperatures that exist in an LED environment. How will it hold up? You can see positions on the circuit where you have high-voltage electrolytics. On the primary side, there is a big, bulk storage, 10 microfarad, 400 volt electrolytic capacitor. We also have an electrolytic 22 microfarad, 50 volt output capacitor for ripple reduction. And we have an electrolytic 4.7 microfarad, 25 volt capacitor biasing the controller.

As each of these electrolytic capacitors fail, they will have a different affect on the circuit. We’ll talk more about that later. At the moment, let’s make sure we understand that these components are a standard part of most two-stage LEDs drivers in use today. Let’s look at what happens to these electrolytic capacitors in their high ambient temperature environments and we’ll see why they fail.

The capacitors always operate at full load and at maximum temperature, as mentioned previously. **Fig. 5** shows the lifetime expressed in thousands of hours for aluminum electrolytic capacitors based against the capacitor temperature in degrees C across the bottom. Then we have different kinds of capacitors: red is a low-cost, 2,000-hour capacitor; blue is a 5,000-hour capacitor; and green is a long lifetime, 10,000-hour capacitor.
If you want your capacitor to reach 45,000 hours of life, first you need a very good capacitor because the ambient temperature, shown in the brown area, is what you’d see inside a lamp. Actually you can’t get to 45,000 hours with an electrolytic capacitor because it will fail at 85°C at 40,000 hours. What’s happening inside the capacitor is that the dielectric material — a combination of a liquid and a filler — evaporates over time and the capacitor starts to lose capacitances. After a certain period of time and much faster in an increased temperature environment, the capacitor fails.

What this shows is that in a high-temperature LED environment, even capacitors rated for 105°C can’t reach the lifetimes that designers need to make an effective LED power supply. This is a clear indication of why we have seen early failure in many power supplies. These LED power supplies are inflicting a very high ambient temperature on the power supply which means the standard the power supply solutions that many people are using simply cannot do the job.

![Fig. 6](image)

Fig. 6 tells us that capacitors have a problem with this ambient. You could partially alleviate the problem by spending more money for longer lifetime capacitors and oversizing them (hard to do in the confined space of an LED lamp), but even if you buy the best capacitor you will struggle to meet the target lifetime in a raised ambient.

Let’s talk about ambient temperatures in capacitors for a moment. The capacitor temperature is determined by the internal ambient — it’s not really determined by the capacitor itself. There is minimal self heating even though the capacitors have a series resistance associated with them. In a typical application, that self-heating is swamped by the heating effect going on around the capacitors. The amount of heating created by the capacitor itself is very small. The internal ambient
is determined by the power density, the power supply efficiency, and the LED temperature, which is controlled by the LED. System efficiency is determined by the power supply, LED temperature by the conversion efficiency of the LEDs and the amount of heatsinking being used. Higher power supply efficiency will enable the system to run cooler.

Bear in mind, of course, that you’re dissipating 100% of the rated power in heat. If you have a very efficient power supply, it’s not going to make much difference. It will reduce heat a little bit because it’s a two-part equation, and you’ll still have a lot more of the power returning to heat than will be saved in a more efficient power supply. The power density of LED lamps reinforces the problem with high temperatures as the heatsinking around the LEDs really ensures that the power supply sees most of the heat from the LEDs.

The ambient temperature outside the lamp might be 25°C. If you look at the ambient inside the 6-inch down light that is inside the can, it might be 45°C. If we look inside the power supply on the solder side of the PCB, it might be as high as 100°C, matched by the output capacitor which also shows a case temperature (Tcase) of 100°C. So you can see that you’re matching the ambient temperature very closely — the capacitor self-heating effect is swamped by external heating from the LEDs. It is worth noting that this power supply has a relatively high efficiency of 80.6%. But the capacitor still gets to 100°C.

Even the best capacitor on the previous chart would last only 15,000 hours at 100°C. So this is not close to the amount of time you need from the circuit. We can see the capacitors are under real pressure inside an LED lamp.

Let’s look at what happens at the end of life for electrolytic capacitors. What happens to your LED lamp when the capacitor fails? There might be a strategy for using electrolytics in such a way that if they do reach the end of their life and begin to lose their capacitance, it won’t affect your lamp too much. We can expect and accept some degradation in performance (remember the LED lamps are allowed to fall to 70% of their output before the end of life). So, some reduction in performance might be acceptable, as long as the lamp still works and emits light.

Let’s look at what happens to electrolytic capacitors in different circuit locations as they approach end of life. First, what do we mean by “end of life” for an electrolytic capacitor? We see that it fails after a certain period of time, but then what do we mean by a capacitor failing?

There are standard definitions of capacitor end-of-life failure: if capacitance falls to less than 25% of its initial value; the amount of power dissipating is greater than 200% of its initial value; its leakage has exceeded the value on the data sheet; when there’s external abnormality and the capacitor starts to swell. If we assume those are the possible failure modes, we can determine if those failures can cause a catastrophic circuit event. To do this, we need to examine the role of the capacitor in each circuit location.
If we look at the high-voltage input bulk capacitor, we see that the end of life gets dramatic. Fig. 7. As the electrolyte evaporates, input current increases, and capacitance begins to fall, resulting in higher and higher peak currents flowing through the primary switching circuit. As the primary current increases, efficiency will fall because the power lost in the MOSFET switches will increase in proportion to the square of the input power. Power losses increase as efficiency falls, adding to the heating effect, and the temperature around the capacitor rises. This accelerates the end of life, causing dramatic reductions in capacitance. As the capacitor starts to die, it changes the operation of the primary power circuitry, increasing the rate at which it degrades.

Eventually, either the circuit won’t start up or the power supply is pushing too much current through the switching MOSFETs which in turn will overheat and fail. In any case, it’s a catastrophic circuit event because the power supply will stop working. You’ll also see EMI on other components with possible unpleasant consequences.

If you look at the comparative EMI plot of the power supply with an input capacitor at the beginning of its life and the plot for the same power supply at end of the capacitor life, you’ll see that the EMI significantly increases as part of the wearout mechanism.
Let’s look at an electrolytic capacitor used in the output stage. Fig. 8. When the output capacitor begins to fail at the end of its life, the failure mechanism is more gentle. As the capacitance starts to reduce, the output ripple current increases. Comparing the plots for the output current ripple at the beginning of the power supply’s life and at the end (when output capacitance has reduced by 50%) we see that output ripple has doubled.

What does an output ripple current do to an output to an LED lamp? Surprisingly little, actually. It doesn’t show up as flicker; it doesn’t stop the lamp from working. All it means is that there is higher ripple on the line. Certain lamp applications already exhibit 100% ripple; low pressure sodium street lights, for example, can accept 100% ripple.

Yes, the output capacitor reaches the end of its life, but so what? The ripple increases, but that does not have a huge impact on the lamp’s operation. In that case, the light will still operate and provide light. It may not provide the light in quite the form that was specified for the lamp when it was new, but it’s still functional, it is still fit for purpose, so it can be considered a relatively a benign failure.

You can see now that the nice thing is that an electrolytic as the output capacitor will continue to operate for a long time. You can actually allow the capacitor to go beyond end-of-life and it will still continue to operate.

A similar effect occurs in the bias circuit. The bias capacitor energy storage will start to fall, but it has to fail quite significantly before it affects the operation of the power supply. You can even oversize the bias capacitor cheaply and take up little additional space because it is usually small to begin with. So, it is not a big deal to use an electrolytic capacitor as a bias capacitor.

Ideally, we want to develop a circuit that eliminates electrolytics completely, or at least eliminates them from the bad places – now we can look for a circuit that is able to do that.
Fig. 9 shows a single-stage combined PFC and CC LED power supply. It doesn’t need a bulk capacitor because it doesn’t attempt to hold the input voltage rail. It doesn’t need an electrolytic primary bulk capacitor on the primary side, so we can eliminate that cause of the lifetime problem. By the way, a quick note on capacitors symbols – notice that these are all straight lines. This means they’re not electrolytic capacitors. Electrolytic capacitors have a curve at the bottom of the symbol. The small capacitors shown here are all ceramics (we will see this in the power supply photograph on the next slide).

So, it’s possible to design a power supply without any electrolytic capacitors at all. This is really good because ceramic capacitors are not going to be affected by temperature like electrolytics are; therefore, this circuit will have a very long lifetime.
Fig. 10 shows a 14 W power supply that has no electrolytic capacitors, delivers over 90% efficiency, and meets PF and THD requirements – all in a PAR38 enclosure – not bad.

If you remember, ceramics have a very, very long lifetime.

This is excellent; we just get away from electrolytics altogether.

But we also saw that using electrolytics on the output side or in the biased capacitor position isn’t a big problem. Maybe a compromise will also work...

12 W Design Using Electrolytic Capacitor in Reduced Stress Location

Fig. 11 shows a 12 W power supply that uses no electrolytic capacitors in the input stage, but does employ them in a reduced stress location. The output capacitor is an electrolytic type because electrolytic capacitors have very high capacitance per unit volume. We have a very compact design with no electrolytic capacitors in a position where end-of-life causes a catastrophic lamp failure.

You still attain a long lifetime because you are putting electrolytics into a part of the circuit where they’ll fail very gradually and gracefully.

Lifetime is a key parameter for lighting. You can’t use standard power supplies because the environment is not conducive to normal power supply operation. You can, however, use a different topology to eliminate aluminum electrolytic capacitors from bad circuit locations. But, if you appropriately task the aluminum electrolytic capacitor, you can still make it work in an extended lifetime application. And we have shown that matching the circuit location with the appropriate capacitor technology is a critical step in extending LED driver lifetime.

You can also use ceramic capacitors, but you really can’t use them to provide bulk capacitance because they’re not volume efficient. To use a ceramic capacitor as a bulk cap for a street light a board area about the size of a suitcase would be required. You can, however, use very small ceramic capacitors that are suitable for the output stage and biasing applications.

The bottom line: The best approach for an LED driver is a circuit topology that does not use a large, electrolytic bulk capacitor.
Also see:

- Ensure long lifetimes from electrolytic capacitors: A case study in LED light bulbs
- Trading off lifetime vs. cost in LED light capacitor selection