BRIDGING THE GAP:
Transitioning from Driving LED Backlights to Driving Solid State Lighting

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The LED has come a long way from its humble beginnings as a simple indicator light to the plethora of applications for which it is used today. Market analysis suggests that it is still early in the LED's "coming out party" and that the next few years will see numerous industries greatly transformed by the introduction of today's higher efficacy, lower cost LEDs. Those of us in the display industry watched as LEDs slowly infiltrated some of the smaller display backlights and recently spread quickly to the medium and larger sized displays. As the LED is adopted into different mediums, special attention should be paid to the way in which the LEDs are driven in order to maximize total value. Although great advances have been made in IC and LED driver design; **there is no *one size fits all* LED driver**. Today's most savvy designers and integrators let their application needs and functional requirements dictate the best type of driver to install in their application. This paper will highlight some of the standard topologies currently employed to drive OEM LED displays and discuss some of the major hurdles that inhibit a generic backlighting driver from being implemented directly into general lighting.

DC to DC LED Drivers for LCDs

Table 1 shows a simplified comparison of the strengths and weaknesses of several LED driver topologies, which should be considered prior to designing/selecting a driver for an LED backlit display. Some of the design parameters that may influence integrated driver selection would include: size, cost, power, noise, dimming, and flexibility.

Topology Style		Single Current Source				Multiple Current Sources		
		Linear Current Source	Hysteretic Current Source	PWM Buck Current Source	PWM Boost Current Source	PWM Voltage Boost & Linear Source	Adaptive PWM Boost & Linear Source	PWM Boost & Hysteretic Source
DC to DC	Pros	Small size, economical, high dimming ratios, very quiet circuit	High efficiency, high power apps, high dimming ratios	High efficiency, high power apps, less noise than hysteretic	Vin < Vout (which most OEM LCDs require), high efficiency, economic	Small size, economical, high dimming ratios	Small size, efficient, economical, average dimming ratios	High efficiency, high power applications, high dimming ratios
	Cons	High power dissipation → low power apps, lower efficiency	More expensive, larger package, more noise than linear	Limited dimming ratios w/out modification, larger package	Limited dimming ratios w/out modification, relatively noisy	High power dissipation → low power applications	Medium power dissipation → medium power applications	Most expensive, larger size

Table 1

Often the driver topology will be partially dictated by decisions made higher up in the supply chain (for example, LED string configuration). This phenomenon is in no way unique to the display industry and factors into other areas of solid state lighting (SSL). SSL is the largest and perhaps fastest growing potential market for LED applications; however, making the transition from driving LEDs from a DC source for displays to driving LEDs from an AC source for SSL products is not as simple as adding a bridge rectifier and a capacitor. There are several unique considerations, such as power factor correction (PFC) and EMI, which must be fully understood when taking this step.

AC to DC LED Drivers for SSL

IEC and ANSI have defined requirements for power factor and input current harmonics and these requirements vary depending on application. Power factor is defined as the ratio of real to apparent power being consumed by an electronic device. When powering a resistive load with a sinusoidal input voltage, the resistive load input current will be proportional to and in phase with the voltage. When the input current consumed by an electronic device is linearly proportional to and in phase with the input voltage, as with a purely resistive load, the power factor is said to be unity or 1 (***see fig. 1a***). A power factor of unity is ideal because it reduces distribution losses and contributes little noise and distortion to the line.

When a load is composed of either non-linear or reactive circuit elements, the power factor deviates from unity. If a load is linear, capacitive, and resistive, the input current will lead the input voltage (***see fig. 1b***). If a load is linear, inductive, and resistive, the input current will lag the input voltage. In either case, the apparent power (the instantaneous product of voltage and current), will not equal the actual power. One reason why agencies such as IEC and ANSI have dictated that real power and apparent power must have a minimum level of “synergy” is that many power utility meters measure apparent power.

Bridge rectifier and bulk capacitor in AC/DC converters:

The majority of single phase power supplies designed before the adoption of power factor and current harmonic guidelines consisted of a bridge rectifier and capacitor, which would convert the incoming AC into a DC with some ripple. That ripple would then be filtered out by additional passive filters or active regulators creating smooth DC power. While this circuitry is cheap and simple to implement, the combination of bridge rectifier and bulk capacitance consumes nearly all of the input current during a very brief period when the sinusoidal input voltage waveform is at its peak, creating a highly distorted input current waveform (***see fig. 1c***). This input current waveform, consisting of many harmonics while in phase with the input voltage, reduces the efficiency of the power distribution network. In addition to this reduction in efficiency, line voltage waveforms become distorted at their peak (during input current draw, when loaded by devices with this converting circuitry), deviating from a purely sinusoidal waveform.

Fig 1a – 1d: Power Factor
Input voltage is represented by the blue line and input current is pink.

Fig 1a – Unity power factor.

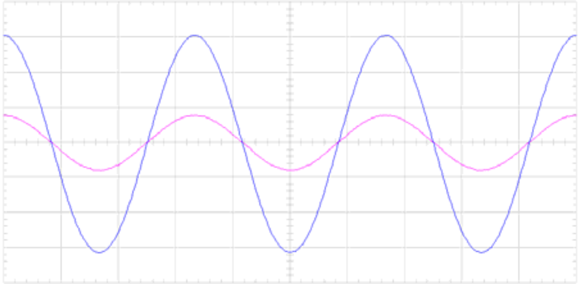


Fig 1b – Non-unity power factor. A 90 degree phase shift between input current and input voltage is the result of a capacitive load.

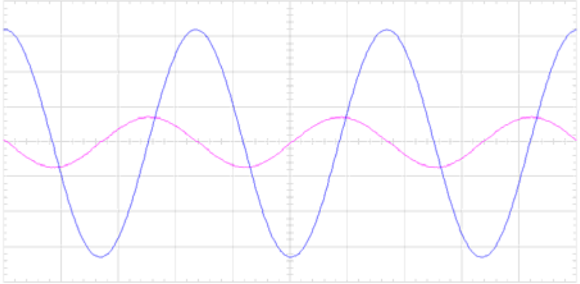


Fig 1c - Input voltage and current waveforms typical of the bridge rectifier and bulk capacitor combination.

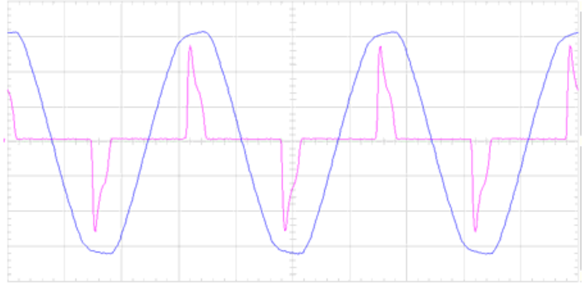
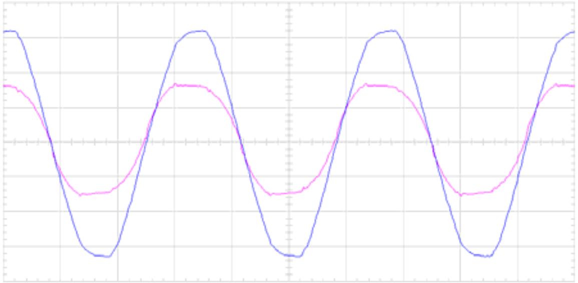


Fig 1d – Typical input voltage and current waveforms for a PFC circuit.

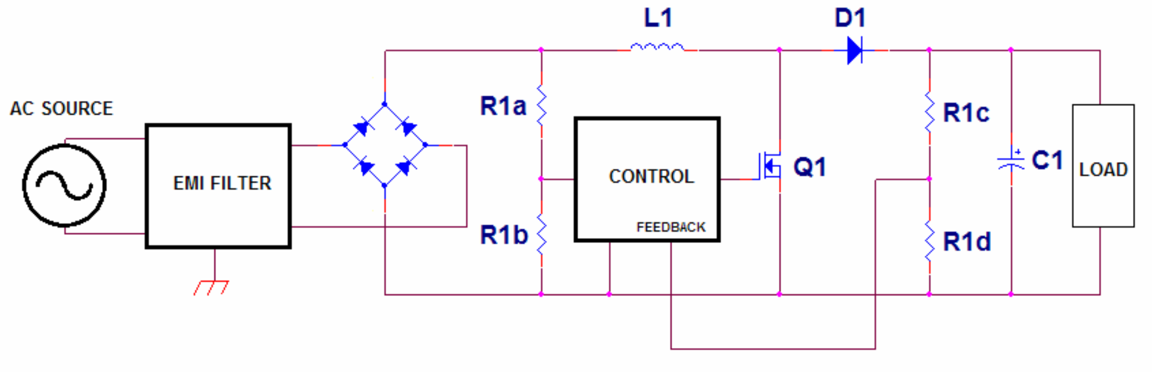


Power factor correction circuit:

In order to reduce the input current harmonics that the bridge rectifier and bulk capacitor AC/DC conversion circuit create, and to keep the current drawn by the power supply in phase with the input voltage, a circuit very similar to ***fig. 2*** can be utilized. This circuit is based upon a pulse width modulating boost converter.

The main difference between the PFC circuit and the boost circuit is that the PFC circuit modulates its input current consumption in order to create an input current waveform that approximates that of a resistive load. In ***fig. 2***, this input current shaping is achieved by sampling the input voltage (in the US, a 120Hz rectified version of the input voltage) and modulating Q1 on time so that the circuit consumes a nearly sinusoidal input current that matches the input voltage in frequency and phase. The resistive network seen in ***fig. 2*** is not always the scheme used for determining the correct modulation of input current, but a popular one nonetheless. PFC circuits generally require a large amount of output filtering capacitance (C1), as they pass a large amount of low frequency to the output when modulating the input current. These circuits also generate very high output voltages, typically 200V or more (they can only *boost* the 110 or 220V coming in!), requiring the addition of a conversion stage between the PFC output and the load circuitry. In addition, nearly all switching converters connected to the line require a complex filter at their input to reduce the noise they generate back to the utility and to filter the noise coming off the line. The specifics of this filtering circuit will be discussed later on.

Fig. 2 – Non-isolated PFC stage



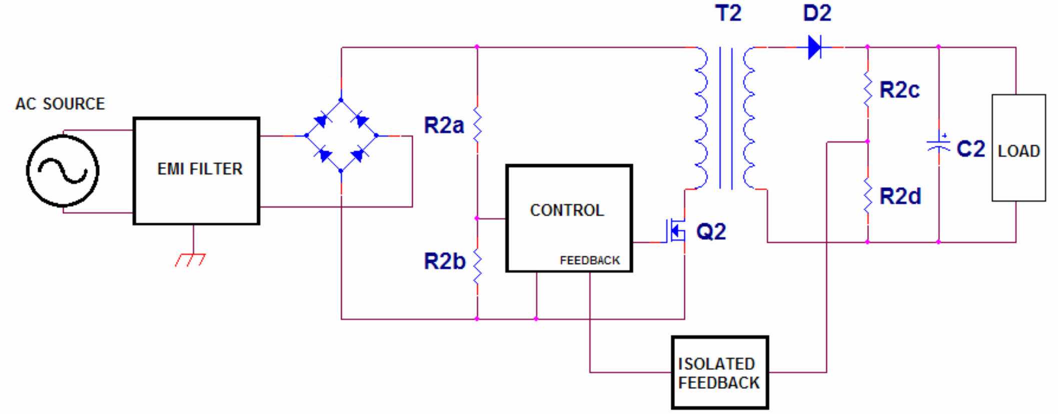
The two-stage approach to AC/DC conversion:

The loads an AC/DC converter will power often run on 48V or less (nowhere near the 200V a non-isolated PFC converter will output in many cases). Therefore, a DC/DC converter (usually one that isolates the output from the input via a transformer) generally follows the PFC and is used to convert the high voltage output from the Power Factor Corrector to a voltage or current suitable to drive the load. The advantage to this configuration is that the converter driving the load directly is supplied with a mostly DC input voltage, allowing the supply to have high input rejection and high load regulation. If properly configured, the power stage is capable of driving multiple LED strings and providing an isolated output. One drawback to this configuration is that the losses from PFC and DC/DC converter are in series, typically limiting the efficiency to the high seventy and low eighty percent range. As LEDs are a disruptive technology, and much has been said about energy savings inherent in switching to SSL, driving at a high efficiency is critical. This configuration also requires the electrical componentry and board layout space for two power converters.

Power factor correction circuit with low voltage output:

One way to limit power supply footprint and part count is to change the configuration of the PFC from a boost to a flyback converter, and to add a stage of isolation to the feedback network. This circuit (***fig. 3***) achieves AC/DC conversion and enables the PFC stage to create an output voltage that is greater or less than the input voltage. The circuit also achieves output isolation, which is necessary in many general lighting applications. The flyback transformer (T2), in which power is transferred from line to load, operates nearly the same as the boosting inductor in ***fig. 2*** with current flowing in the primary during Q2 “on time” and in the secondary during Q2 “off time”. Considering input current, the main difference between the boost and flyback configuration is that the flyback circuit does not draw current when Q2 is off. The rest of the circuit operates the same as a non-isolated boost PFC. This configuration, if properly implemented, can achieve efficiencies in the high eighty to low ninety percent range, and has reduced cost when compared with the two-stage approach. Poor line rejection and mediocre load regulation are inherent to this circuit’s operation; therefore, it is only recommended to drive loads that are not highly susceptible to moderate ripple and voltage variations like LEDs. This circuit forms the basis of a single string current source, as well as a multiple string current source, which will be discussed shortly.

Fig. 3 – PFC with Isolated output



Those with experience driving LEDs know that a voltage source is not a driver, for LEDs should be driven by a constant current source. Indeed, this low voltage output does require additional hardware to provide the constant current for the LEDs. Regardless of how you label it, this style of low voltage output is a popular mode of powering LEDs, as it allows the integrator a great deal of flexibility with the load and reduces the number of different power supplies that have to be stocked. For example, a lighting designer may configure from 1 to 11 strings of up to 6 or 7 LEDs to a single 100W, 24volt, single output power supply. Of course, each string requires a constant current provider. The alternate method is to use a power supply that includes a constant current source onboard, but you need one for each string of LEDs that you wish to drive. Both methods have several advantages and disadvantages as shown in Table 2.

		Input		Single Output	
		2-Stage AC to DC	Single Stage AC to DC	Constant Voltage	Constant Current
AC to DC	Pros	Relatively simple circuits: Boost Non-isolated PFC & Isolated DC to DC, high load regulation, flexible	Fully isolated flyback PFC, Highly efficient ~90%, economical, smaller sizes possible	Allows for a great deal of flexibility - can "drive" several strings in parallel, stock fewer part numbers	Driver is optimized for the load → highest possible efficiencies
	Cons	Inefficient (2 stages in series) → ~80%, requires 3 stages for multiple output driver → ~70% relatively large, potentially more expensive	More complex circuit, poor line rejection & load regulation → loads should not be susceptible to ripple/voltage variations	Requires additional hardware to provide constant current, stocking 1 part number → may be more power than you need	Driver is specific to LED string configuration, lack of flexibility
	Apps	Applications requiring tight output regulation with very quick transient response	General lighting, very high efficiency requirements (for energy savings payback: street lighting, parking, high bay, refrigeration, etc.), smaller package requirements, cost sensitive applications	For lighting integrators handling a large variety of lighting configurations with multiple strings	High volume applications, applications requiring the highest efficiency

Table 2

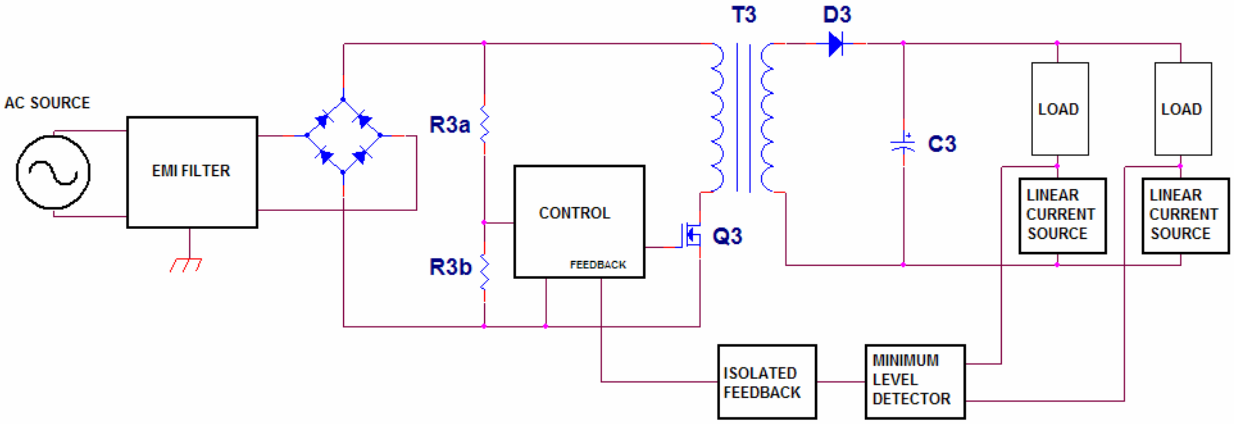
Power factor correction circuit with current output:

With a simple modification that converts the output voltage feedback network to an output current feedback network, the power factor correction circuit in ***fig. 3*** will maintain a constant output current as opposed to a constant output voltage. This change in feedback configuration is identical to that between the PWM voltage boost and PWM current boost (both driven by DC as opposed to AC sources, and neither requiring output isolation). As with the PWM boost, this circuit will only drive one LED string. As discussed for the previous circuit, the single stage approach will not achieve the input rejection or load regulation that the two stage approach is capable of, but as an LED string is a static and insensitive load, only marginal output regulation is required. Moderate PWM dimming ratios are achievable, although LED current amplitude modulation as opposed to pulse width modulation may be required in many situations. The drawbacks of PWM dimming are currently the subject of debate by many engineering and also healthcare professionals.

Adaptive Power factor Correction circuit with linear outputs:

In order to drive multiple strings with an AC input, one might consider integrating a feedback scheme similar to the adaptive PWM boost circuit introduced in ***Table 1*** with the PFC controller, in order to drive multiple strings of LEDs. The PFC portion will work the same as the low voltage circuit above, but regulate its output voltage based on linear current source headroom levels. This circuit will work best in lower power applications and applications where there is adequate heat sinking. Excellent dimming ratios are achievable with this circuit utilizing PWM. The discrete linear current sources, with fast transient response, adequately reject line and regulate the load.

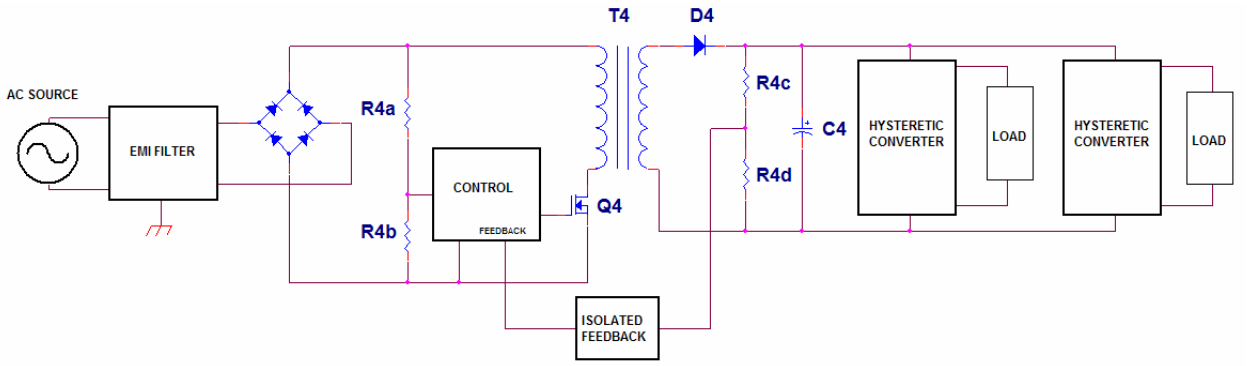
Fig. 4 – Adaptive PFC with multiple linear current source outputs



Power factor correction circuit with hysteretic outputs:

For higher power multi-string applications, a variation on the previous circuit, with hysteretic converters and a fixed voltage output PFC, is feasible. This circuit maintains the high efficiency and excellent thermal characteristics of the hysteretic output stages, while achieving extremely high dimming ratios with PWM, along with the excellent line rejection and load regulation of the linear current sources above.

Fig. 5 – PFC with multiple hysteretic current source outputs

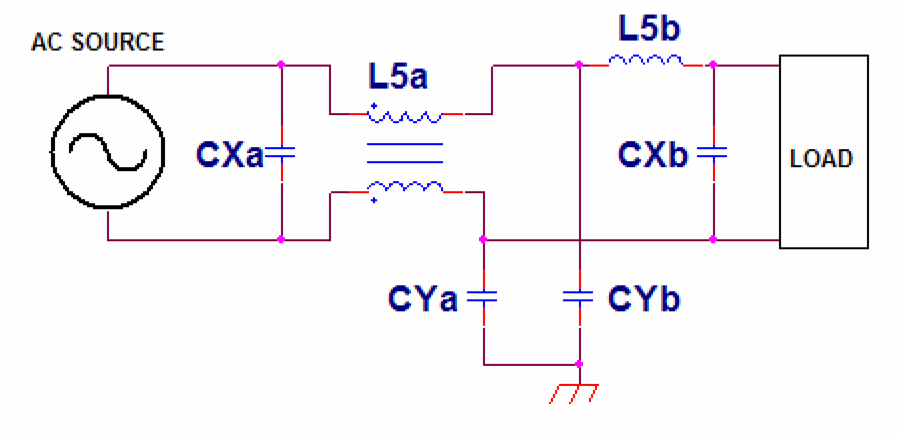


EMI filter:

EMC norms dictate maximum conducted and radiated emissions that electronic devices can create to be in the range of hundreds of kilohertz to tens of megahertz. In addition to the limitations on emissions, electronic devices are required to meet defined levels of immunity to conducted, and radiated interference signals. Devices must also repeatedly survive transient surges of energy in order to work reliably when powered off-line. To achieve compliance with these norms and insure reliable operation over device lifetime, a passive filter (***see fig. 6***) is generally utilized as an interface between the wall source and AC/DC converting power supply. This filter, generally consisting of a common-mode choke (L5a), a differential mode choke (L5b), "across the line" capacitors (also known as "X" capacitors [CXa, and CXb]), and "line to ground" capacitors (also known as "Y" capacitors [CYa, CYb]), is capable of filtering common and differential mode noise generated by the utility, along with differential mode noise generated by the AC/DC converter.

Common mode signals, which present themselves on both AC input terminals of the circuit, will be filtered and passed to earth ground by the combination of L5a, CYa, and CYb. L5b and CXb act as a differential mode filter, creating a very low gain voltage divider to high frequency noise present on only one of the input terminals, and passing low frequency input current. L5b and CXa filter noise created by the load (in our case, the power factor correction circuit). This noise is typically switching noise created by the main power device turning on and off. The combination of L5b and CXa acts like L5b and CXb, but in reverse, impeding the high frequency noise created by the load from reaching the utility. There are many variations of this circuit, all designed to filter the noise created by and present in each device's environment. EMC testing often reveals inadequate configuration or component value choices in a supply, requiring an iterative process of modification and experimentation.

Fig. 6 – EMI Filter



Conclusion:

As LEDs continue to gain acceptance in more and more applications, the demands on the driver continue to increase. This presents unique challenges and opportunities for driver manufacturers working to keep pace with lighting designers and integrators. The key to getting the best value from SSL is to understand that no one topology is the answer for all applications. There are a variety of different topologies, each providing the best solution for certain applications, and the desired results of the application should be considered at the outset when choosing an LED driver design.