

Facts about Dimming

Over 95% of the existing residential and commercial electrical dimming infrastructure are single channel wall dimmers. Gregg Sheehan, IP / R&D Engineer at Light-Based Technologies explains why it is crucial to serve the market with high quality solutions and how to solve the upcoming challenges.

This article is intended to address “direct” phase-cut dimming of LED fixtures and does not include the wide range of network type dimming systems such as DMX, DALI, 0-10 or 1-10VDC style control networks or theatrical methods. This is primarily because there has, to date, been much written discussion on the use of LED fixtures in network control, yet less that addresses the larger part of the dimmed lighting environment – namely the use of the ubiquitous single channel wall dimmer that makes over 95% of the existing residential and commercial electrical dimming infrastructure. Those acquainted with the subject matter are familiar with the need to maintain power factor, efficiency and stable operation but the challenges to achieve these goals are less well understood.

In short, single channel phase-cut dimmers are a significant part of the existing lighting landscape and show no signs of going away. In fact, sales of these dimmers continue to increase. According to studies done almost 9 years ago there were 4-billion incandescent lamps in the US alone with estimates of over 150 million traditional dimmers installed. The forecast is for these to continue to increase in numbers well into the future and be installed into buildings and homes world-wide. The impetus behind this continued adoption is two-fold – a desire for increased illumination aesthetics in increasingly upscale residential/commercial environments and the possibility for “energy savings” via dimming. As the

various “green-mandated” world governments move towards legislating traditional incandescent/ fluorescent fixtures out of existence, these same sockets will ultimately be populated with LED lamps as replacements. This latter point needs to be underscored as the lamp fixture most likely replaced first in a given installation is the one that creates the most value, and of these, many will likely also be connected to some form of single channel dimming solution or controller. The existing wall dimmer with an incandescent lamp works quite smoothly and looks very appealing. It is aesthetically pleasing and economical in its implementation. This is the benchmark LED dimming needs to hit and then surpass, to be fully embraced by the end user. Unfortunately, dimmed LEDs often do not fare so well. Substantial power savings alone can’t make these facts invisible to the end user who is looking to re-create the effect and response of their existing lighting infrastructure. The fact that the US Energy Star criteria offer as a solution a request that LED lamp suppliers provide a list of suitable dimmers for their lamps is sufficient evidence that the compatibility of LED with existing dimming technology is far from perfect.

The two major types of phase-cut dimmers used today (so-called because they remove or cut, selected portions from each AC half-cycle wave) are leading-edge dimmers (LEDIM) and trailing-edge dimmers (TEDIM). See Figure 1a, b and c. LEDIM seems to be prevalent mostly in North America. TEDIM is very popular in the EU/ and the rest of the world, supposedly working better with low- voltage halogen lamps using electronic

transformers. LEDIM usually employs a simple Triac or Triac/DIAC as the active element, while TEDIM has generally more complex circuitry and utilizes MOSFETS or IGBTs as the active device(s). LEDIM could be said to be Active State ON and TEDIM to be Active State OFF, relative to a zero degree starting point, per 180 Deg or half-wave. It is fair to say that there is slightly less inherent noise produced by TEDIM, as RF and EMI from TEDIM’s active state, as it is switching off, rather than on, with less overshoot and resultant high frequency noise.

Figure 1:
Phase cut
dimming types
Achieving “Good
Dimming” with
LEDs

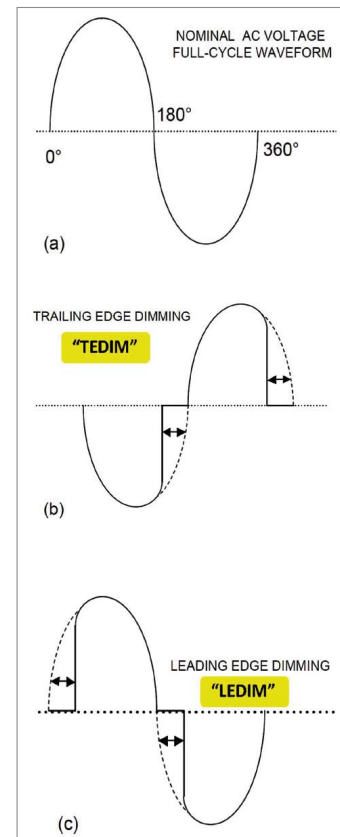
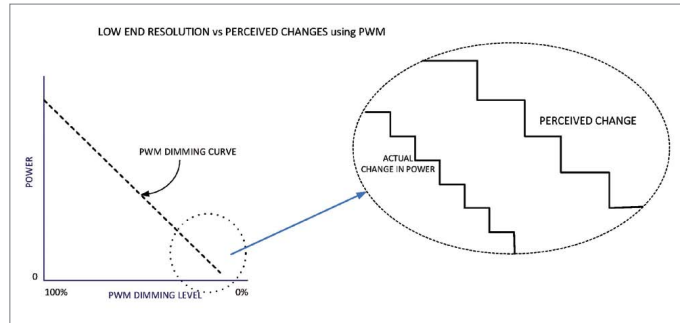


Figure 2:
PWM resolution
at low dimmer
settings



The lighting industry, inclusive of LED fixtures and lamps, generally has clearly defined electrical standards, properties, life expectancy, temperature and light distribution standards, which are defined and endorsed by the third-party certification industry, (including the IES LM-79 and LM-80 (now referenced by DOE as Energy Star™)). It does not, however, have the same definitions and standards for actual dimming performance over the dimming range.

The practical benchmark in the industry is still the behavior of a typical dimmer with an incandescent load. This response just appears to be "right" to the average user's eye/brain-response (psycho-visual perception) to be fairly linear and smooth in performance. This smooth flicker-free dimming response is beneficially assisted by thermal inertia of the filament in the lamp and visual persistence in our vision system. The relationship between lamp output optical power and our visual response is in fact a log curve for an incandescent lamp running from a 100% light level down to a 0% light level. However, when many LED fixtures are dimmed they can shut off completely at around 10% to 20% light level on the dimming scale due to practical limits imposed by their power supply minimum-voltage requirements. Furthermore, at low power levels there can be a transition region in the dimming process/range which causes flickering or visible transitions, as the LED goes through increasingly larger steps such as in a standard Pulse Width Modulation (PWM)-type system. The PWM steps are the same size but our visual perception makes them

larger (shown in Figure 12) as a comparison between perceived light levels vs. absolute power/light levels. Compared with the ideal, this is visually distracting and unacceptable.

Consider restaurants: They are the quintessential dimmer users, with the business norm being that lighting is in some dimmed mode, usually within the bottom 20% of the full-light level, to create the traditional intimate dining experience. They use a nearly theatrical approach, to create areas of high luminance contrast ratios by having a low level background between tables with often a highlight lamp or central candle placed on the table to create pools of lighting. After closing and during the day they may also require 100% lighting levels for cleaning, and next day preparations. Also consider movie theatres. They have a clearly defined need for safety- mandated, minimums and maximums, as well as building code requirements. This low level "norm" area, is where PWM-style dimming starts to show its warts, as it starts running out of bits and acts in a large "step" transition mode, resulting in flicker and unsmooth light changes (see Figure 2).

The most elegant solution for dimming is the use of intelligent linear control. This method offers compatibility with virtually all dimmer types and manufacturers, and greatly simplifies the compliance under Energy Star™ with the ability to dim smoothly throughout the full range. Energy Star™ currently has no specific requirements other than listing which specific equipment makes and models that will work together successfully.

A further refinement and advantage of one such proprietary approach offered by Light Based Technologies is the ability to scale a lamp's response in a programmable way that enables finer, repeatable control over a specific area of the entire dimming range. This ability to change modes, while using a standard third-party dimmer is made possible by detecting changes in the dimmer control when doing short, repeated or specific motions. For example, a quick up/down, done in under a second, flips the mode to a different preset mode, such as Mode "B" or 40% maximum light level at full fader or full clockwise and counter-clockwise rotation of a control. Figure 3 shows how the actuation of this proprietary "Deep Dimming" feature creates a magnified dimming resolution at the bottom of the dimming range such that the bottom 20-50% of full range is spread out over the entire electro-mechanical adjustment range. This is irrespective of the user input device or dimmer and allows for much finer control of settings that operate normally in a low dimmed setting. The control interface may be a rotary potentiometer, linear fader, capacitive sensor or "touch" type user- interface.

Another set of solutions in this application of intelligent linear control, is the ability to have multiple actual-performance curves available, including logarithmic, linear and custom variants. They are selectable by a similar method, shown above. Figure 3 shows three sets of "S"-type or incandescent-style performance curves for example, with a different maximum level on each. Mode "C" for example would be ideal for restaurant use during business hours and Mode "A" would then be enabled for both after-hours cleanup and the morning prep. Mode "C" would allow the management to really fine-tune the exact atmosphere they desire for their business, by manipulating the light levels throughout a room.

Another aspect of linear control is that the current is generally fixed at a lower level than with PWM, which operates by varying duty cycle and thus average current, over the same ΔV as linear

Figure 3:
Magnified
dimming range

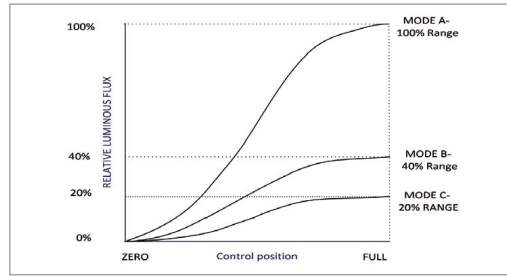


Figure 4:
Current versus
voltage

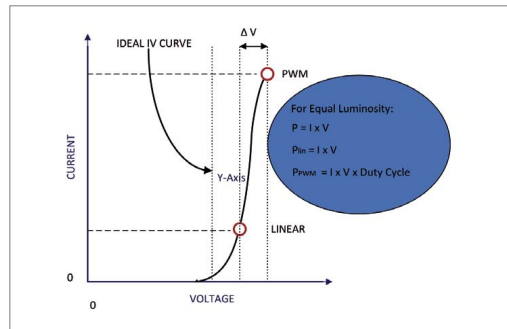


Figure 5:
Typical "Droop"
in output for LEDs
as a function
of forward
current. (Source:
Candlepower
forums)

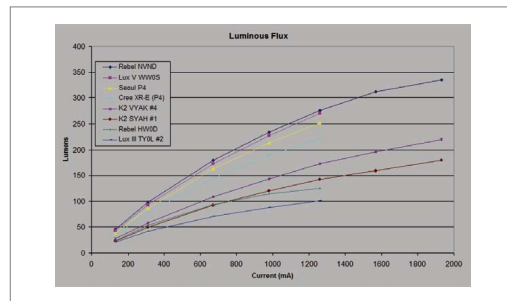


Figure 6:
Comparison in
output efficacy
at low dimmed
levels for dimmed
PWM versus linear
(Luxeon Rebel
Data)

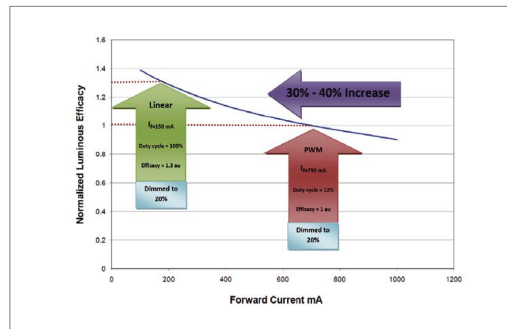
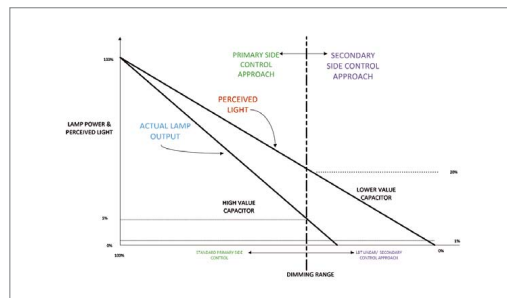


Figure 7:
Advantage of
linear secondary
side control



operates. The net result is less power consumed and greater efficiency with linear controls characteristic reduced forward voltage (see Figure 4).

The use of intelligent linear control as an overall control technique shows further advantages, particularly when applied to low level light-dimming applications. The well-known LED output "droop", inherent at higher currents is not present by virtue of the true reduction of instantaneous junction current. This effect is significant in that it represents up to a 30 to 40% improvement in overall efficacy as the lamp is dimmed (see Figure 6). This mode of operation also delivers optimized energy efficiency through most dimmed light levels when compared to traditional PWM approaches. Figure 5 shows the "droop" (departure from linearity) for a wide variety of popular LED manufacturers for luminous flux versus forward current, at constant junction temperature.

Figure 6 offers a more focused analysis on efficiency. It clearly illustrates the change in overall efficacy of a typical Luxeon™ Rebel LED operated between PWM and linear operation at a typical 20% electrical power dimmed level. Here the effect of current droop is significantly more apparent in the overall LED efficacy (assuming constant junction temperature). Both systems are dimmed to an effective 20% electrical power level while the efficacy of the linear dimmed system (100% duty cycle, 150mA) is 30% higher than that of the PWM dimmed system (20% duty cycle, 750mA).

Linear Control

Most switching-type power supply (SMPS) or LED driver topologies involve designs with separate primary and secondary "side", or sides as in the case of multiple output supplies, and these are usually electrically/ physically separated by a transformer or fly-back inductor.

Nearly all major semiconductor companies making power supply or LED driver control IC's, espouse the very same technique of primary-side control. However, the direct secondary-side control of power supply or LED drivers has many practical advantages, as shown with the LB4 technology from LBT.

As visible in Figure 7, it can be seen that with PWM control topology, the perceived light output is still at 20% when the actual power is dimmed to 5%. The linear approach goes very near to zero perceived light output, when the actual power is reduced to zero. This would substantiate the common PWM product specifications claims of dimming from 100 to only 10%.

As can be seen, the relationship between measured light output power and the perceived amount of light is quite linear, with an exponent of 0.5, from Stevens' Power law.

LBT also uses a patent pending method to send time-relevant control info from the primary to secondary sides, which enables low delay or real-time control. Having the



Street light in China Shandong



Ledlink Optics, Inc.

With integration of optical design, mould tooling, and mass production in house, Ledlink offers professional optical solution and various types of semi-module products.

Our mission is to provide just in time services along with cost effective and optimised performance secondary lens for innovating LED lamps.

Please contact us for further information or visit our website for our latest products.

Asian Olympic Games in China Guanzhou



Trade center in China Sichuan



Stage lighting & acoustic exhibition in UK



Bridge lighting in Poland



www.ledlink-optics.com
service@ledlink-optics.com
 T: +886-2-8227-6126
 F: +886-2-8227-6127

Single Lens



Multi Lens



Street Lighting Lens



Asymmetry Lens



Convex Lens



COB Lens



Certification : ISO 9001 ISO 14001 UL:E335300 RoHS

Figure 8:
Linear dimming
comparison chart

direct load controller on the secondary side, also allows accurate delivery of load current and minimum voltage, and only when required. The differences, shown in Figure 7, include low-end resolution, less capacitance required from improved regulation, etc. Two well-known controller IC manufacturers have successfully reached 0.1%, as in one case, with the inclusion of large value capacitors, with their low MTBF, higher cost and size issues. Another manufacturer achieves this by ignoring electrical isolation requirements.

Dimmer Holding Current

Another factor to consider for proper dimmer interoperability is that all leading edge-type Triac-based dimmers (LEDIM) require a holding current due to their internal electronic component's internal architecture and behavior. In short, they will shut off completely when current stops going through them, causing the light to flicker or even turn off during this time, depending on the driver's ability to restart. This of course, occurs periodically, every time the AC waveform approaches or leaves the zero-voltage region.

In many designs, a holding current can be simply created by a small, simple resistor load, but this is a fixed value active throughout the entire waveform duty cycle, which unnecessarily wastes energy. A truly efficient holding current circuit is a solution, which is only turned on when there is insufficient load current and in an appropriate minimum amount and at the particular time for the load and dimmer current requirements. This requires a design which is both dynamic and periodic, to perform the function efficiently, such as the proprietary LBT Holding Current design. This is a practical solution as Triac holding current requirements do vary substantially, according to the Triac component wattage, semiconductor materials variations and the OEM manufacturers' internal component construction.

Figure 9 shows a Spice simulation illustrating both the dynamic and periodic response of Light Based

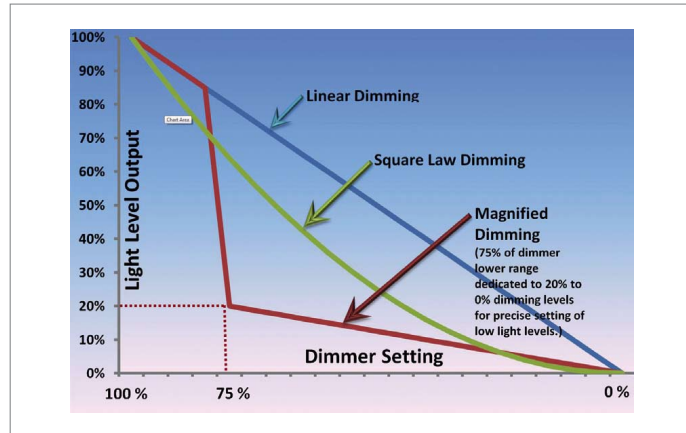
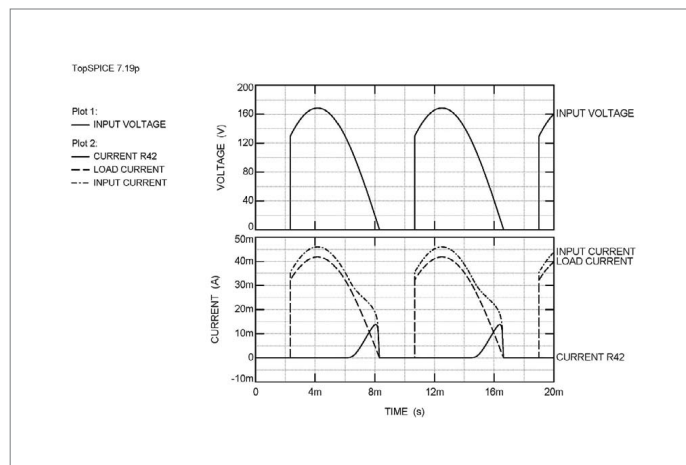


Figure 9:
Illustration of
dynamic holding
current



Technology's approach. The actual amount of dynamic holding current (Current R42) is actively determined by both the load requirements and the requirement of the individual Triac or semiconductor dimming device. The portion of duty cycle from approximately 8 to 11 ms has a suitably low impedance and very small current, in order to suit the Triac minimum requirement. A LEDIM-type dimmer AC half-wave waveform is shown at top for reference at approximately 25% dimming from full, measured post bridge-rectification, but pre-filtering.

Trailing edge dimmers or TEDIM also require holding currents but for different reasons. The active devices are usually MOSFETS or IGBTs. The devices will also stop working properly when there is no voltage drop across them, which also happens periodically

during the waveform. The off-transition will have a slightly gradual slope rather than a near instantaneous slope. The result is that all dimming behaves poorly without a suitable holding current, leading again to the need for a dynamic holding current to deliver smooth operation and maximum power efficiency.

Power Efficiency

Every element of an LED lighting system has its own efficiency figure and to date there is no such thing as 100% efficiency. Every component in the system has an energy loss including the driver/ power supply, the LED itself, the optics (lenses or diffusers), and reflectors (where used) and of course, poor thermal management, which can cause a gradual change, usually downward, in luminous output produced at the LED gap itself, over time.

As a consequence, when any of these specific components enjoys an increase in efficiency, even in the range of single-digit percentages, the contribution to overall efficiency is significant. Due to the relative cost differences in technology and the relative immaturity of LED fixture development and productization, engineers are more motivated than ever, to make as many improvements as possible; more so than the humble, and soon-to-be- obsolete, incandescent/ CFL fixtures enjoyed during their own development cycle.

In general terms, power supply/driver units may be characterized for efficiency, by:

$$W = P_{\text{out}} / P_{\text{in}} \text{ or } W = V * I_{\text{out}} / V * I_{\text{in}}$$

In simple terms, the driver efficiency is:

$$\text{Efficiency [\%]} = P_{\text{out}} * 100 / P_{\text{in}}$$

The LED efficacy: lumen/W

The lens refractive index or general transparency percentage (t[%]):

$$n = \frac{\text{velocity of light in vacuum}}{\text{velocity of light in medium}}$$

or

$$t[\%] = I_{\text{m out}} \times 100 / I_{\text{m in}},$$

respectively, and the reflector efficiency from

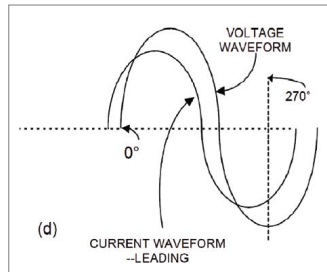
$$\frac{I_{\text{m out}} (\text{incidental}) \times 100}{I_{\text{m in}} (\text{incidental})}$$

Considering system efficiency throughout the dimming range is a necessary consideration. Does a modern Triac-type dimmer, used for LED and drivers, have an efficiency specification? Good question! Old-fashioned dimmers used loss resistive elements while modern dimmers are more like triggered switches, particularly the MOSFET-type. Still, nothing is perfect and everything has some ESR (electrical series resistance) which wastes power by producing heat. During normal operation, dimmers do get warm to the touch. Phase-cut dimmer electrical efficiency is typically around 99%. The other 1% is dissipated in the dimmer as heat. So a dimmer on a 600W load

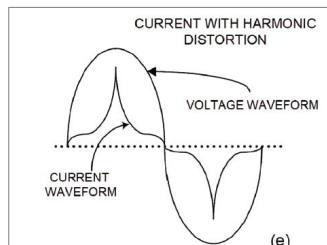
would produce around 6 watts of heat, and a 1kW load producing 10 watts. UL/CSA -specified temperature limits on surfaces dissipating this waste heat is typically 140F (60C) degrees.

The Importance of Power Factor

Power Factor refers simply and in a perfect world, to the degree to which the voltage potential and current draw required by the load, are in-phase or co-incident, for each half-cycle of the sinusoidal AC waveform. Both should happen at the same time, much like in a purely-resistive load does. It is defined as real power over apparent power. The “type” of load can cause the current to lead or lag in time, relative to the voltage waveform time-base (see Figure 10).



Dimmers of both styles have a major effect on Power Factor, for all types of loads (capacitive, inductive, resistive, Linear, non-linear and combinational/or complex). This is because it is typical to cut voltage phase over the current peak in the same area as required by the load causing imbalance and harmonic distortion on the AC line (see Figure 11).



“Distortion power factor” describes how the harmonic distortion of a load current decreases the average power transferred to the load.

Distortion power factor (DPF):

$$\text{DPF} = \frac{1}{\sqrt{(1+\text{THD}_1^2)}} = \frac{I_{1\text{rms}}}{I_{\text{rms}}}$$

THD₁ is the total harmonic distortion of the load current. This definition assumes that the voltage stays undistorted (sinusoidal, no harmonics). This simplification is often a good approximation in practice. I_{1rms} is the fundamental component of the current and I_{rms} is the total current; where both are root mean-square values.

$$\text{PF} = \text{DPF} \times \frac{I_{1\text{rms}}}{I_{\text{rms}}}$$

The result when multiplied with the distortion power factor (DPF) is the overall, true power factor or just power factor (PF).

Poor power factor is rarely evident to the residential end-user however the commercial/ industrial-level user may pay additional surcharges. If their load is highly inductive, for example, they may have to install capacitor switch banks to compensate for this power loss. At the residential level, the utility company must spend money on hardware and additional power to correct for this imbalance throughout their distribution system.

LED drivers and switch-mode power supplies (SMPS) are considered to be non-linear or complex loads and require power factor correction (PFC) to reduce the non-sinusoidal current distortion they create, from having excess energy at harmonics of the line frequency of the voltage (see Figure 11).

The EU standard EN61000-3-2 regulates harmonic content and basic PFC criteria for all SMPS. Passive PFC in LED drivers/power supplies usually involves adding capacitors, resistors and steering diodes, such as “valley-fill” circuits. Active PFC also involves redistributing the current over the voltage half-cycle waveform. The problem to solve is how to improve load regulation without adversely affecting PFC or make the load look like a linear resistor. The typical technique is to utilize a 2-stage supply/driver topology such as boost, buck or buck-boost.

Figure 10:
Example of current waveform leading the voltage waveform

Figure 11:
Distortion Power Factor waveforms caused by non-linear/complex loads

LBT's new proprietary power-supply/ LED driver currently under development utilizes a radical new topology to improve Power Factor performance and efficiency.

Power versus Perceived Light

The relationship between actual dimming (light reduction) and perceived dimming (human perception of light reduction) is logarithmic by nature (see Figure 12). Dimming to say, 25% of the original full light output is perceived as approximately 50% dimming and so forth. That being said, a typical dimming amount of 3 to 5 % dimming shows up on the last little bit of fader or rotary control adjustment is hardly ideal. A narrow dimming range is barely perceived. Human perception of audio behaves in a similarly logarithmic way, where larger amounts of power and change proportional to

that power are required, in order to be perceived. Modern LED technology in retrofit lamps can just barely achieve the high level of brightness and quality that is acceptable for the mainstream market. Much work remains to push the envelope of brightness, power, efficiency and thermal management for commercially acceptable products. The good news is that strides continue to be made in this direction and LBT is happy to be on the cutting edge of innovation, in this truly exciting field.

On the most pragmatic level, dimming LED lighting saves money, in several ways. This happens from reduced direct electrical consumption and reduced maintenance or replacement costs, through to increased lifespan of the light fixture, itself. Every dimmer automatically saves 4-9% in electricity-even at the highest lighting levels-over a standard on-off switch. And when

users choose to dim their lights, even more electricity is saved. Due to Triac triggering characteristics, they do not turn on exactly at the zero crossing of the AC waveform and there is a small amount of phase cut occurring, until that voltage threshold is reached, even at the fully-on setting.

A summary of aesthetic performance attributes for high performance LED dimming would be: Controllable dimming range, programmable dimming curve, smooth transitions, good starting and warm-up, stable light level throughout the adjustment range, stable color or programmable color shift during dimming, low acoustic and EMI noise, control/ user input flexibility, good Power Factor and pleasing, comprehensive color control.

Good technical performance attributes for high performance LED dimming are: wide-range AC input operating voltage, wide input waveform acceptability, highest efficiency possible, flicker-free and step free low range performance, no cut-out, smooth full-range operation from 0 to 100%, low harmonic distortion (THD), good Power Factor, low-EMI and RF generation, minimum voltage operation, current regulation and low inrush current.

Dimming LEDs, like the less-efficient CFL, is difficult. Through careful explicit design, they can be made to perform identically, to what the end-user is familiar with, using traditional incandescent phase-cut dimmer controls. ■

Figure 12:
Perceived light level versus absolute power/light levels

