Controlling LEDs

Technical white paper
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1 Abstract

Ten years ago, Light Emitting Diodes (LEDs) were used primarily in niche applications as status indicators, and in exit signs. Today, they're designed into nearly every lighting application from street lights to stairwells. However, owners, contractors, engineers and designers do not always know how to control LEDs or they have had a negative experience. Additionally, the fast-moving state of the LED lighting industry means there is a lot of risk that needs to be managed throughout a job. This white paper provides:

- An overview of LEDs and types of LED products
- Advantages and limitations of LEDs for general illumination
- Benefits of dimming LEDs for occupants/home owners
- Important considerations for dimming LEDs

Unlike fluorescent loads, most LED products are inherently dimmable. However, the dimming performance can vary greatly from manufacturer to manufacturer, or even in different fixtures from the same manufacturer.

The overall goal of this paper is to help you to take advantage of rapidly advancing LED technology in a way that makes your projects more successful.

2 Executive Summary

LED lighting technology is rapidly progressing, and it is very important to know how to control LEDs to ensure success for the end user and to achieve energy savings.

An LED is an electronic device (chip) that produces light when an electrical current is passed through it. There are two distinct type of LEDs: the LED lamp (also called a LEDi or retrofit lamp) and the LED fixture.

LED drivers are low-voltage devices that convert the line-voltage 120/220/277 V power to the low voltage needed for the LEDs, and may also interpret control signals to dim the LEDs. LED drivers come in either constant current or constant voltage. These two types of drivers are NOT interchangeable, and it is the design of the LED load that determines which driver is appropriate. Both LED lamps and LED fixtures require LED drivers. Selecting the proper LED driver determines:

- The control type needed to dim the fixture
- The best possible dimming performance
- Potentially, the maximum operating lifetime of the LED product

There are many advantages to LEDs such as high efficacy (lumens per watt), product longevity, and lower heat load, and LED products are available in many sizes and shapes. Benefits of dimming LEDs for end users and occupants are energy savings, space flexibility, enhanced safety, and increased productivity.

You can either switch or dim LEDs, depending on the use of the space. If dimming is preferred important considerations include:

- Dimming range of LED products (100 to 20% vs. 100 to 1%)
- Dimming performance and expectations (smooth, continuous, flicker-free)
- LED fixture and driver standards
- Dimmer standards
- LED driver features
- Minimum and maximum loads for LED drivers and controls

There are many control options when it comes to LEDs, with the most common options being:

- Two-wire forward phase
- Two-wire reverse phase
- 3-wire forward phase
- 0-10 V
- EcoSystem® digital
- DALI digital
- DMX-512

Once these considerations are addressed and the control type is determined, it is then important to consider the components (and subcomponents) of the system and how defective product and performance issues will be resolved.

After the system is up and running, the expected life and the long-term support of all the components becomes the critical factor.

3 Introduction

3.1 What is an LED?

A Light Emitting Diode (LED), also referred to as SSL (Solid State Lighting), is an electronic device (chip) that produces light when an electrical current is passed through it. The wavelength (or color) of light that is emitted is dependent on the LED materials. LEDs are available in many colors, including red, blue, amber, green, and near-UV colors, with lumen outputs ranging from 10 lumens to 200 lumens per watt.

For signage, TVs and theatrical applications, Red/Green/Blue (RGB) LEDs are each combined in varying intensities to create any visible color.

The LEDs used predominantly in general illumination architectural applications are “Phosphor Converted Blue” LEDs - blue LEDs that have a yellow phosphor placed over the LED. The phosphor absorbs some of the blue light, and emits light in the yellow, green, and red portions of the spectrum.

When the unabsorbed blue light mixes with the other colors of light it creates what your eye perceives as “white” light. The choice of blue LED and yellow phosphor, and the method of placing the phosphor, creates hundreds of colors of “white” due to differences in color temperature and CRI (Color Rendering Index).

A single LED chip is mounted with other chips, in many different forms, to create LED modules (also known as LED Arrays, LED Engines, or LED Tapes).

3.2 Types of LED products

There are two distinct types of LED lighting: the LED lamp (also called a LEDi or retrofit lamp) and the LED fixture.

LED lamps typically have screw-in, Edison-base sockets meant to replace standard incandescent or screw-in CFL lamps. There are also LED lamps to replace other sources used in chandeliers or accent lights. In all cases, the bases of these lamps have integral drivers that determine whether or not the lamp is dimmable, and also determine dimming performance.

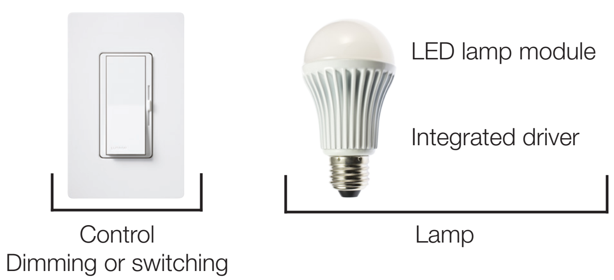


FIGURE 1: LEDi (LED retrofit lamp) and control must be compatible

LED fixtures vary from cove lights to down lights to pendant lights and troffer fixtures, and they usually have a driver mounted within the housing or remote from the LED source. Fixture manufacturers usually offer different driver options (for the same fixture) to support different control technologies (phase-control vs. digital) or applications (dimmable vs. non-dimmable).

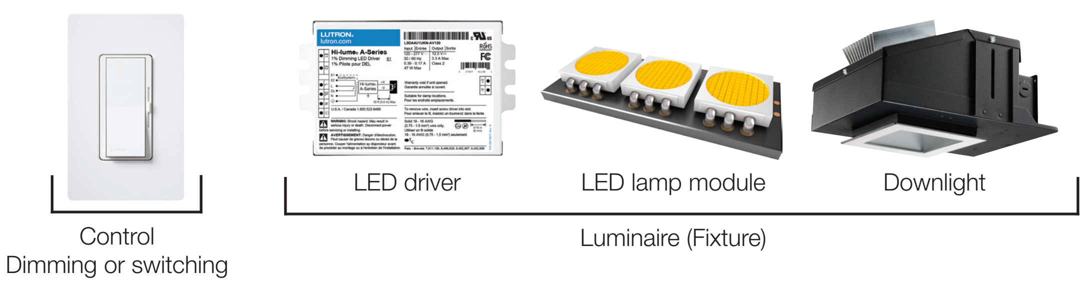


FIGURE 2: LED fixture (with driver and LED lamp module) and control must all be compatible

3.3 LED Drivers

LED chips are inherently low-voltage devices that need additional electronic components to convert the line-voltage 120/220/277 V power to the low voltage needed for the LEDs. These electronics may also interpret control signals and dim the LEDs accordingly. These devices are referred to as LED drivers.

LEDs are powered by one of two different types of drivers. LED driver outputs may be constant voltage (usually 12 V or 24 V) or constant current (e.g. 350mA, 700mA or 1050mA). It is the fixture manufacturer that chooses the driver type and configuration to match the electrical requirements of the LED module they chose to use in the fixture

Constant voltage drivers provide a fixed constant voltage to LED modules connected in parallel. A constant voltage driver is used in areas where you may have a variable amount of fixtures, such as a cove (LED tape) or under-cabinet light. These are similar, or sometimes identical, to electronic or magnetic low voltage power supplies used as remote transformers for halogen strip lights in a cove (or those used with MR16 lamps/fixtures). They typically have 12 V or 24 V outputs, although other output voltages are possible. Constant voltage drivers can only be dimmed via a PWM method.

FIGURE 4: Constant voltage driver example

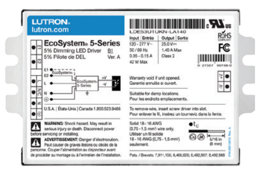
Constant current drivers provide a constant current, such as 700mA, to a specific LED module that is designed to operate at that current level. This is great for a down light, sconce or other LED fixtures that use only one LED module per driver (much like a fluorescent lamp with its associated ballast). Note that some drivers support multiple currents, making them more flexible when the manufacturer is designing a fixture. For constant current drivers, there are two different dimming methods for adjusting the output current when dimming: pulse-width modulation (PWM) and constant-current reduction (CCR) (refer to Lutron Application Note 360 for more details).

FIGURE 3: Constant current driver example

Constant current and constant voltage drivers are NOT interchangeable, and it is the electrical requirements and the design of the LED load that determines which driver is appropriate. Often this is application-based, but it is still the configuration of the LEDs that determines if a constant current or a constant voltage driver is needed. Drivers are sometimes manufactured to operate specific LED devices or modules, while others can be configured to operate most commonly available LEDs. Generally, it is up to the fixture manufacturer to specify the proper driver type to be used.

The selection of an appropriate driver is not limited to just making sure it matches the LED module being used. **The driver is the primary component that determines the best-possible dimming capabilities of the LED lamp or fixture.** Furthermore, the LED driver is one source of potential failure for the LED fixture. The long-life benefits of LEDs are significantly reduced if the driver is not specifically designed for an equally long life.

Beyond compatibility with the LED load, LED drivers must be selected to fit the mechanical constraints of the fixture. For example, Lutron's LED drivers come in a variety of different form-factors to fit a variety of different fixture types, regional practices, and applications:



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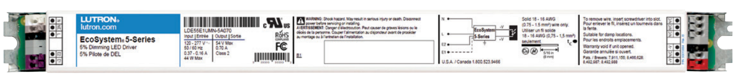

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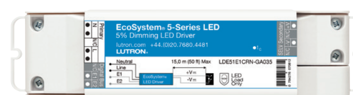

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4 Why Dim LEDs?

4.1 Advantages and limitations of LEDs for general illumination

Advantages

- **High Efficacy:** Measured in Lumens per Watt(LPW) LED-based lighting fixtures can achieve efficacies ranging from 25LPW to over 100LPW (up to 300LPW in some circumstances), compared to a halogen/incandescent efficacy of 5-15LPW or a fluorescent efficacy of 5-90LPW.

- **Longevity:** LEDs can achieve useful lifetimes ranging from 25,000 hours to up to 100,000 hours, compared to ~1000 hours for an incandescent or 15,000-40,000 hours for fluorescent.

- **Lower BTU heat load:** LEDs do not create IR (heat) radiation in the occupied space, and generate less heat overall than other light sources.

- **Smaller size and format:** LEDs are available in many sizes and shapes—allowing existing fixtures to be smaller and enabling totally new fixture types.

- **LEDs do not contain hazardous materials:** as compared to mercury in linear fluorescent or CFL lamps.

Limitations

- **Higher cost:** High Brightness LEDs, necessary for general illumination, are expensive but dropping in price. They also require electronic drivers to convert conventional AC voltage to discrete DC voltages for the LED modules.

- **Color and color rendering:** LEDs vary widely in apparent color (Color Temperature) and how they affect the color of objects and people in the space (Color Rendition). Color stability over time is another potential limitation.

- **Control-compatibility challenges:** Due to the wide range of LED-based lighting product types, not all LED lamps are dimmable, and the ones that can be dimmed may be limited in dimming performance and system compatibility. In fact, lighting has become a "system" where the LED module, the LED driver and the LED dimmer must be chosen by the lighting fixture manufacturers and the design team with system compatibility in mind.

4.2 Benefits of dimming LEDs for occupants/end users

Controlling daylight or dimming an electric lighting source is very important, so that a restaurant, theater, residence, hotel lobby or presentation space can create the environment that the designer intended, and enhance the ambiance for the end user.

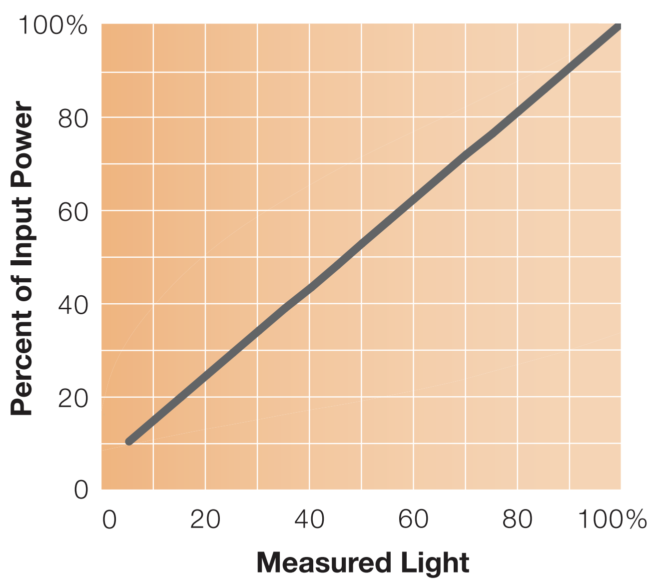


FIGURE 5: Power vs. Measured Light for a typical LED driver

Similar to fluorescent, incandescent, halogen and low-voltage lamps, dimming LEDs saves energy at a roughly 1:1 ratio. If you dim LEDs down to 50% of their light output you will save nearly 50% of your energy usage. Not only do you save by using a more efficient source, you save even more energy by dimming LEDs.

Dimming LEDs also makes them run cooler, which extends the life of the electronic components of the driver, as well as the yellow phosphor on the LEDs. This will extend their life and increase the LED's lumen maintenance (the slow decrease in light output over a light source's lifetime). Research is ongoing to better quantify the relationship of dimming LEDs and lifetime extension.

Dimming LEDs offers many other benefits common to other lighting, including:

- **Space Flexibility:** Dimming control systems provide for space flexibility—what may be an office space today could easily be converted into a call center tomorrow; or a gymnasium can be used as a theater or cafeteria just by adding dimming control for the lighting. Your home and your workplace should be designed to complement your needs. As your needs change throughout the day, your lighting should adapt as well; bright enough to read a book, but dim enough for computer use. Whether you are at home or at work, lighting control can create a comfortable atmosphere to support your activities throughout the day. If daylight is available, the LEDs can be dimmed to save even more energy.

- **Enhanced Safety:** Lighting controls can enhance the safety and security of your office and home by automatically dimming or raising light levels upon entering a stairwell or hallway. Security systems or fire alarm systems can turn on lights in case of an emergency. You can also control both interior and exterior lights from the car as you approach your driveway to ensure optimal visibility and comfort.

- **Increased Productivity:** Lighting control can increase productivity by allowing the user to select the right level needed for varying tasks, and reduce eye strain and fatigue. Proper lighting enhances your ability to work at peak performance for more of the day, or allows students to focus more effectively at school.

5 Important Considerations when Controlling LEDs

5.1 Switching LEDs

The most basic form of control is line-voltage switching. Switching can be used in energy-management systems with occupancy and daylight sensing. Fixtures or zones supplied with multiple control circuits can also utilize multi-level switching. In a multi-level switching installation, portions of a fixture or zone of lights can be turned off or on based on the needs of the space. Since an abrupt on/off of the illumination is associated with switching, it is primarily utilized in applications where adjustable light levels or particular aesthetics are not required, e.g. a warehouse.

5.2 Dimming range of LED products

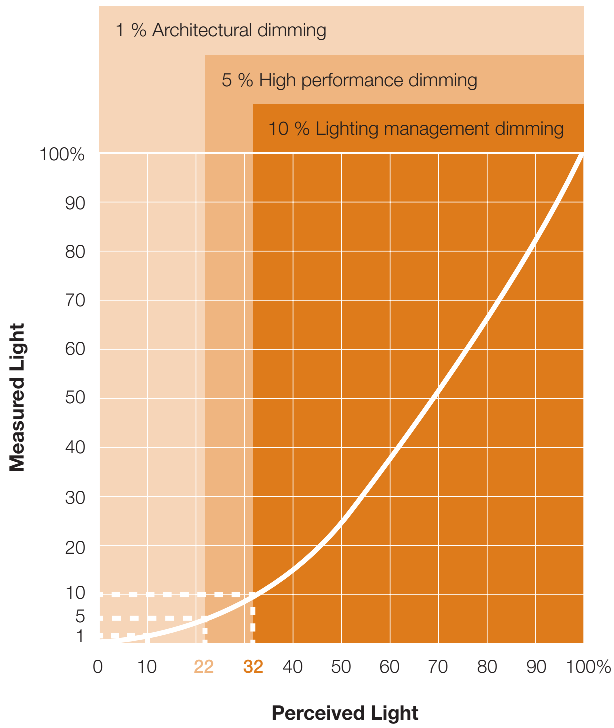
All incandescent lamps dim well below one percent perceived light, which looks like an orange filament glow, and this sets the expectation for all dimmed light sources. Conversely, the dimming range of an LED lamp or fixture can vary greatly from one device to another.

Some LEDs may dim to a minimum level of only 20%, while a different product may dim to 1%. Additionally, manufacturers will quote measured light levels, e.g. 10%, but consumers are not familiar with perceived light. What is the difference?

- **Measured light** output is the quantifiable value of light (measured in foot-candles) by a light meter or similar device. This is the dimming ratio percentage indicated on LED product specification sheets.

- **Perceived light** is the amount of light that your eye interprets as a result of pupil dilation. The eye's pupil dilates at lower light levels, causing the amount of light to be perceived higher than measured (e.g., 20 percent measured light equals 45 percent perceived light). The equation for determining perceived light is the square root of the measured light percentage (e.g. $\sqrt{0.20} = 0.45$).

As the designer or the end-user, you need to select the dimming range of your fixture or lamp that will be suitable for your application. A product that dims to 20 percent measured light (45 percent perceived) may be the energy-saving solution necessary for the daylight harvesting strategy needed in an office, but 20% dimming wouldn't make sense in an Audio/Visual media room where 1% dimming is expected.



Formula: Perceived Light (%) =

$$100 \times \sqrt{\frac{\text{Measured Light (\%)}}{100}}$$

FIGURE 6: Measured vs. Perceived Light

If an LED fixture spec sheet does not state the dimming range, you should contact the manufacturer for that important piece of information. Lutron testing report cards (found at www.lutron.com/LEDTool) include perceived light as well as measured light, to provide all the information needed to align customer expectations.

It is important to understand that the dimming range of any LED product is based solely on the driver. **The integral driver of a screw-in LED retrofit lamp and the external driver of an LED fixture will determine how low the connected LED module is capable of dimming.** Furthermore, different drivers may produce different dimming curves, even if they can dim to the same low-end light level. Often, there is no guarantee that relative light levels will match between LED products from different manufacturers, even at the same dimmer level.

The driver alone (whether internal to the lamp or an external driver) not only determines the lowest possible low-end light level, but also the best possible dimming performance, whether it is smooth and continuous, or steppy and full of flicker.

Finally, be aware that the dimming range of an LED product may vary based on what type of dimming control is used. **Using the wrong control, even if the driver is capable of providing outstanding dimming performance, can lead to poor dimming quality due to incompatibility between the driver and control.**

5.3 Dimming performance and expectations

The public's experience with incandescent dimming is that it is smooth and continuous. Specifically, any change in the control (dimmer) position should be reflected by an equal change in light level—there should be no abrupt changes in light level as the light source is being dimmed. Each manufacturer defines dimming in a different way, but the end user expects that the dimming will not be distracting or have noticeable, irregular changes in light.

Even more important is eliminating flicker in the dimming range. Flicker is the unexpected modulation of light level that is visible to the human eye. It is more susceptible in LEDs because of the extremely fast change in light output caused by the LED chip reacting to changes in input current in microseconds. Flicker can come from many sources, including line noise, control noise, component tolerance and poor LED driver circuit design. Flicker can be continuous (happening all of the time), or intermittent (only happening some of the time or at certain light levels). A good driver should account for all of these internal and external factors and still provide flicker-free, smooth, continuous dimming. A properly designed LED dimming driver should not allow flicker at any time or any light level, nor have any of the following additional problems:

- **Pop-on:** After being dimmed to a low light level and switched off, sometimes LED lamps or LED drivers will not turn on until the dimmer's slider is moved up to 20, 30 or 40%. This is referred to as "pop-on," which is especially challenging in 3-way situations where lights must be able to be turned on/off from different locations, not just from the main dimmer.

- **Drop-out:** There should be no drop-out. The light should only turn off when the dimmer is turned off. This can be achieved by utilizing the low-end trim settings available on many wallbox and system-level dimmers to ensure that the lights remain on at their lowest light level at the bottom of the dimmer travel.

- **Dead-travel:** Adjusting the dimmer control without a corresponding change in light level is disconcerting and undesirable.

- **Audible Noise:** Buzzing from the lamp, driver or dimmer is unacceptable.

- **Shimmer:** Small changes in light intensity, usually noticed at medium to low light levels, and often only at the periphery of vision. Often, the terms flicker and shimmer are used interchangeably.

Note that LED lighting, like fluorescent lighting, does not inherently change color when dimmed. Traditional incandescent and halogen lamps dim to a warm (more orange) color as they are dimmed to lower light levels. This is a result of the physical processes inherent in all incandescent lamps.

Left unaddressed, some customers who are used to colors getting warmer when dimmed may be dissatisfied with the static color of LEDs when dimmed. Therefore, some manufacturers are simulating the performance of an incandescent load by mixing white, amber, or other colors, allowing the LED lamp to mimic incandescent color changes as it dims. The effectiveness and methodology of this simulation may vary widely from manufacturer to manufacturer. Mixing sources from multiple manufacturers may provide inconsistent and undesired performance.

5.4 LED Fixture and driver standards

Certification by a Nationally Recognized Testing Lab (NRTL), such as Underwriters Laboratories (UL), CSA, or Intertek, is an important aspect of ensuring the safety of any product, and LED luminaires are no different. Such certifications confirm that a fixture has passed standardized tests and establishes that a product should not present any unexpected hazard upon installation.

Many types of products are components that have been tested to a particular safety standard, but are intended to be installed as part of a larger, finished assembly. These components are considered “recognized” (such as “UL recognized”, abbreviated as RU).

Finished products that are intended to be installed as stand-alone products are considered “Listed” (such as “UL Listed). Many LED drivers are tested and marked as a “recognized” component, because they are intended to be installed as part of a complete LED fixture (which would then get the “Listed” marking). In the past, fluorescent dimming ballasts were “UL Listed” and could be used in any fixture.

The differentiation between Listed and Recognized components is important. In order to get a Listed mark on an end product, such as an LED fixture, not only does the manufacturer need to perform a complete battery of tests (including, but not limited to, thermal tests), but they must also provide a detailed breakdown of many of the components that go into its construction, including Recognized components. This means that after the testing has been completed, the manufacturer is NOT free to make a substitution from one Recognized component to another, if it was not included as part of the original testing. For example, a manufacturer cannot replace one LED driver with a second driver if the second driver was not included in the test report on file with the NRTL being used. Furthermore, a driver cannot be substituted by the installer and still maintain the proper Listing of the end product. Different drivers may only be used if additional testing is done and records updated appropriately at the NRTL.

A recent change to LED fixture standards has been the introduction of a “TL” certification for LED fixtures and drivers. This allows a fixture manufacturer to test its fixture to a particular temperature standard in conjunction with drivers that have a TL certification. If done properly, manufacturers that have fixtures that meet the TL requirements can freely substitute drivers that also meet TL requirements, with little or no additional testing or paperwork necessary. Increased market adoption of products that meet TL requirements should enable fixture manufacturers to more easily offer a wide selection of different drivers that meet their customers’ needs. TL temperatures will be selected based on UL concerns about safety—each driver manufacturer will select temperatures that best allow them to warranty their product.

In certain fixtures, using a Recognized driver is not practical, as there is no complete fixture to get fully UL Listed. For example, LED strip or tape light comprises only of a driver, i.e. a power supply, and the LED load itself. In this case, a Listed LED driver is necessary. Again, this type of driver has been tested to meet all the necessary safety certifications when used in a stand-alone configuration. This means that one Listed LED driver can be freely substituted by any other Listed LED driver, either by the manufacturer or the installer, as long as the proper output electrical specifications (voltage, current, power) are met. Besides LED tape light, Listed LED drivers may be desirable in many situations where LED drivers are remote mounted and offered separately from the fixture.

5.5 Dimmer standards

Like fixtures, dimming controls are tested to various standards developed and executed by NRTLs. Part of the testing for dimmers involves testing for specific load types, because different load types are subject to different electrical stresses. For example, MLV loads are susceptible to overheating if presented with non-symmetrical waveforms. Therefore, dimmers that are rated for MLV loads are specially tested to ensure they don't create asymmetrical waveforms. Dimmers that are designed only for incandescent loads are not required to pass the symmetrical waveform test, and therefore may damage any MLV loads that are connected.

To prevent unsafe situations, the National Electric Code (NEC) requires that all dimmers be used only with the type of load they were designed, tested, and marked for use with. If a dimmer is not marked for use with a particular load type, it must not be used on that load type. LED load types don't fit the existing profile of any existing load type for a variety of reasons:

- LED fixtures (screw-in lamps or fixtures with drivers) dimmed with phase-cut waveforms present stresses to a dimmer that can exceed the stresses that would not be generated by an incandescent load. At best, this can cause premature failure of the load or control; at worst it can create an unsafe situation.

- The internal construction of LED lamps and drivers can vary widely. Two LED products of the same wattage can create two very different stresses on a control.

Testing standards have not commonly defined a standardized LED load against which any dimmer can be tested. Instead, they have required dimmer manufacturers to test individual LED loads to ensure the safe operation of the dimmer. **Because of the differences in LED loads, positive test results with one load cannot be generalized to many different loads.**

Because older incandescent-only phase-control dimmers were not tested or rated on newer LED loads, their reliability and safety is unknown in those situations. Repeated testing has shown that LED loads, in many cases, will cause higher stresses on a control than an incandescent load of the same wattage.

Fortunately, most manufacturers have developed dimmers made especially for dimmable LED loads. These dimmers have been tested to properly and safely handle the additional stresses that LED loads may cause, and typically have LED load-specific ratings (such as 600W incandescent and 150W LED). Furthermore, they have been tested on many different LED loads, and the results are typically publicized as part of a compatibility list. A lack of an LED-specific load rating does not necessarily imply that the control is not suitable for LED loads. Check with the control manufacturer or spec sheet to ensure that using the control with LEDs is allowed.

There are few standards that exist regarding compatibility between drivers and LED loads. NEMA SSL-7A is one standard which provides for basic interoperability between LED loads and phase-control dimmers. Using dimmers and lamps that are compliant with this voluntary standard will provide some assurance of basic dimming performance. However, SSL-7A compliance alone is insufficient to ensure the dimming performance will meet the needs and expectations of customers.

5.6 LED Driver features

The nearly instantaneous response of LEDs to changing current makes them highly susceptible to flicker, especially compared to incandescent sources. One of the most important LED driver features (regardless of whether the driver is constant current or constant voltage) is the quality and consistency of the DC output voltage of the driver.

Remote mounting of a driver (mounting the driver external to the LED fixture, from ten to hundreds of feet away) could result in potential voltage drops, power losses, or noise susceptibility on the DC wiring that, if unaccounted for, will be reflected in unstable or lower-than-expected light output from the LED module in the fixture.

5.7 Minimum and maximum loads for LED drivers and controls

Proper loading of each component in an LED system is critical. First, selecting an LED driver for use with a fixture must ensure that the LED load is less than the driver's maximum rating (typically in amps, volts, and/or watts), AND is greater than the driver's minimum rating. The LED driver may operate intermittently, or fail prematurely, if not properly loaded.

When controlling LED drivers, consideration must be taken to ensure the dimmer control is operated within its rating (typically in watts, W). For example, the number of lamps able to be installed on a single-phase control dimmer may seem like an easy question to answer; however, when using an LED load, a 600W incandescent dimmer with a 15W LED lamp does not necessarily mean 40 lamps (600 divided by 15) can be used on this dimmer. While the LED lamp may only draw 15W continuously, it may have a start-up inrush current or repetitive peak current during every half-cycle that makes it appear much worse, i.e. act like a higher wattage load. That 15W LED lamp can cause the same stresses on the dimmer as a 60W incandescent load. If you exceed 150W using 15W LED lamps, you may overload the dimmer. These stresses are why the LED-specific load rating of controls designed for LEDs is usually less than their incandescent load rating.

Neglecting this transient current puts significant stress on the dimmer, exceeds the dimmer's design limits, and may cause premature product failure or undesired system performance, such as excessive acoustic noise. Lutron has observed that some LED loads can act as the electrical equivalent of up to a 100W incandescent, even for LED loads that are less than 20W.

Not only are maximum loads important, but a minimum number of fixtures may also be required for some dimmers, due to the 25W to 40W minimum load that most incandescent dimmers require to operate correctly under all conditions. When using incandescent lamps, minimum load requirements were easily met with only a single lamp. However, with LEDs, multiple loads may be needed on some older dimmers in order to meet the required minimum load. Dimmers designed and rated for LED loads usually have a much smaller minimum load rating, sometimes as little as one or two lamps (regardless of lamp wattage).

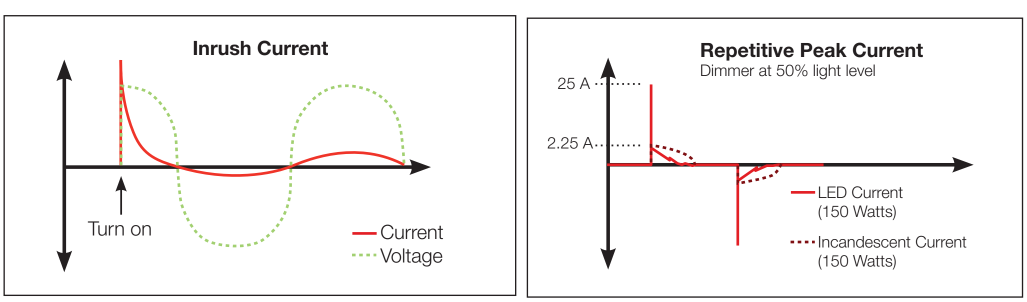


FIGURE 7: Inrush Current and Repetitive Peak Current

5.8 LED Control Options

Dimming control technologies refer to the signal and wiring between the dimmer control on the wall and the LED driver in the fixture or the LED lamp. LED retrofit lamps generally only use forward or reverse phase control technologies; some more modern LED lamp designs may also use wireless control. LED fixtures may use any method. The control type is independent of the driver output type (constant current or constant voltage).

The compatibility of a dimmer with a particular LED fixture begins with making sure they both use the same control method, whether a simple stand-alone wallbox dimmer or a more complex lighting control system is being used. Dimmers that use one control method may also include wireless technology within the dimmer to communicate between loads or as part of an entire home or building lighting control system.

The following are the most commonly used control methods used to dim LED loads:

- **Two-wire forward phase (leading edge) control:** Typically used for incandescent and magnetic low-voltage (MLV) light sources, this is the most common method of dimming control. The National Electrical Manufacturers Association (NEMA) estimates that there are over 150 million forward phase-control dimmers installed, and many of these are likely to control LED replacement lamps as incandescent bulbs get replaced.

  Working well with forward phase control is critical to the success of LED lamps. Unfortunately, most currently-installed controls were never designed for LED loads and are not UL listed to operate them. Their performance is hit or miss and, in many cases, will cause LEDs to flicker, drop out, pop on or not dim to low levels. These dimming controls may also require multiple lamps per control in order to meet the minimum load requirements. The safety and reliability of incandescent-only controls has not been tested or certified by a manufacturer or independent test lab.

  Newer forward phase control dimmers, specially designed to reduce or eliminate the problems seen with controlling LED loads, are UL listed with hundreds of specific LED loads, ensuring acceptable dimming performance. Most LED-specific controls are available for simple replacement of existing incandescent-only controls.

- **Two-wire reverse phase (trailing edge) control:** Typically used to control electronic low-voltage (ELV) light sources, reverse phase control is often effective on capacitive loads such as LED drivers. While it does not have nearly the installed base that incandescent dimmers have, this ELV control type is sometimes specified as the only supported control type for some particular LED loads.

  Reverse phase controls almost always require a neutral wire to power the internal electronics, and not every electrical back box has a neutral present. Installing reverse phase dimmers in older buildings may require that a neutral wire is pulled to the box. These types of controls are not as widely available in the marketplace and are generally more costly.

- **3-wire forward phase (leading edge) control:** This control type is used by dimmers that were created originally for fluorescent dimming. Three-wire controls (connections consist of Dimmed Hot, Switched Hot and Neutral) have a separate line-voltage wire that carries the phase control signal separate from the power wires.

Three-wire is more precise than 2-wire control and the signal is less susceptible to electrical noise. There are over 30 years of history in the industry using 3-wire controls to dim fluorescent ballasts to 1% without flicker, drop out, or pop on. To achieve this high level of performance, a third line-voltage control wire must be pulled to the fixture. The same 3-wire dimmer that controlled fluorescent dimming ballasts can be used to seamlessly control LED drivers designed with a 3-wire control input.

- **0-10 V Control (4-wire: Hot and Neutral, plus 2 low-voltage control wires):** This analog control type consists of two pairs of wires:

  1) A 120/240/277 V line voltage switch (class 1 wiring)

  2) Low voltage dimming control (class 2 wiring)

  Line voltage to the LED driver is switched in order to turn the driver on and off. The low-voltage control adjusts an input to the driver by varying the voltage between 1 V (minimum light) and 10 V (maximum light) DC. The driver associates this input low-voltage level to a particular dimmed level of the LED module. Since the control signal is a small analog voltage, long wire runs can produce a drop in the signal level resulting in varying light levels from different drivers controlled by the same control device.

  0-10 V control has been utilized in the lighting industry for many years as a means of mixing and matching dimmer controls from one manufacturer with loads (drivers or fluorescent ballasts) from a different manufacturer. This is particularly important in the growing LED market since the majority of LED driver manufacturers do not also manufacture controls. They therefore rely on 0-10 V technology to integrate their driver with a control system by others. Although 0-10 V control is expected to be a universal control topology, it is possible and common to experience incompatibility between controls and devices. This is because 0-10 V dimming standards for architectural applications in the US do not adequately define electrical characteristics of controls and devices to ensure compatibility. For this reason, many driver and control manufacturers design their products to comply with European IEC standard 60929 annex E, but this standard only defines the electrical interface of the protocol. It does not ensure compatibility or define the aesthetic performance of the dimming, such as a smooth, flicker-free dimming curve, or the low-end light level.

  The best way to ensure compatibility is to design the system with controls and drivers from a single manufacturer, or verify that compatibility testing of the components from each of the manufacturers used in the system has been accomplished. Otherwise, mixing 0-10 V loads from different manufacturers on the same control can lead to mismatched or disappointing dimming performance.

- **EcoSystem/DALI Digital (4-wire: Hot and Neutral, plus 2 low-voltage data link topology-free wires):** The DALI (Digitally Addressable Lighting Interface) standard originated in Europe for control of fluorescent ballasts, but is now also used in commercial buildings in the United States. DALI is defined in IEC standard 62386 for fluorescent dimming ballasts and LED drivers. It allows digital control of individual fixtures, maximizing the user's control and productivity. There is currently no support for controls or sensors tied directly to the DALI link in the protocol, so each DALI manufacturer has to offer a manufacturer-specific DALI implementation in order to support these elements. For example, Lutron offers proprietary enhancements to DALI in the EcoSystem digital lighting control protocol. While the DALI standard is much more robust than the 0-10 V standard, using DALI controls and DALI drivers from multiple manufacturers does not ensure compatibility or matched dimming performance.

EcoSystem and DALI provide addressing of individual fixtures and status feedback from the loads, making it easy to digitally assign occupancy sensors, daylight sensors, time clocks, manual controls and other controls to one or many fixtures without complicated wiring. This opens up an entire suite of energy-saving and system-monitoring control schemes where the design and setup is all done within software, making the electrical and control design and installation simple. Power is circuited separately from control wires, so the 120 V or 277 V circuit can be fully loaded, making electrical design and installation easier.

While digital control of fixtures using the standardized DALI protocol provides great flexibility and the ability to mix components from different manufacturers, limitations to the design of the DALI protocol have led to field problems where DALI components from one manufacturer will not reliably talk to controls from another, despite both being based on the same standard. Furthermore, some customer-desired functionality is not built into the DALI standard, leading to manufacturer-specific extensions to the DALI protocol which only work when controls and loads from a single brand are used. To avoid problems, many specifiers choose to stick with DALI components from a single manufacturer. When compatibility issues arise and multiple manufacturers are involved, it is difficult to know who to turn to for support.

EcoSystem, from Lutron, enhanced the standard DALI protocol to allow more digital fixture and control devices (e.g. wall controls, daylight sensors, occupancy/vacancy sensors) to be used on the data link. EcoSystem is engineered and tested to guarantee compatibility between Lutron controls, loads and sensors. This digital control method allows for guaranteed compatibility and performance, as well as easy re-zoning and reconfiguring without rewiring during the design, commissioning, and building lifecycle.

- **DMX512:** Created initially for use in theatrical applications, DMX512 is becoming more commonly used in architectural lighting applications where dramatic color changing effects are desired. Selected fixtures are usually equipped with RGB (Red/Green/Blue) LEDs and the color and intensity control of the fixture can be changed quickly and dynamically. DMX has 512 available channels per link (called a Universe). RGB LED fixtures typically use a number of these available 512 channels per fixture, but this varies by manufacturer and application. For example, movable fixtures require greater numbers of channels to denote how the fixture should pivot from one location to another. There are also manufacturers who are using DMX as the control type for tunable white LED lighting in general illumination applications. These fixtures can be static or can dynamically change their color temperature throughout the course of the day in an attempt to match the color temperature patterns of natural sunlight.

  Control of DMX512 fixtures typically occurs from theatrical stage boards, dedicated controllers, dimming panels, or DMX interfaces. Wiring, addressing and interfacing of the control system and light fixtures may vary per manufacturer. Furthermore, there are multiple accepted ways for terminating cables and connectors—all of which can add complexity if the designer or installer is not well versed in the use of DMX512 lighting. For best results, contact the fixture or controls manufacturer for more information about how DMX fixtures can be integrated with control systems.

- **RF:** Radio Frequency (RF) technology is a growing technology that manufacturers are using to communicate with LED products. The range of products in the RF category is quite broad—from LED lamps and fixtures with built-in/embedded RF transceivers to separate interface devices with RF transceivers that use one of the other technologies, such as phase control or 0-10 V, to control the

LED or LED driver directly. There are numerous RF communication protocols which can be selected, from manufacturer specific proprietary protocols to open standards, each with their pros and cons. Products that use different protocols are not generally compatible with one another, and typically require interfaces, bridges, or gateways to connect them.

The broadcast frequency of operation of an RF system is an important factor to be considered—designers must pay special attention to existing RF devices that may use the same frequency within the space (such as Bluetooth, Wi-Fi, and Industrial, Scientific and Medical (ISM) band products). Most manufacturers use frequencies around 400 MHz, 900 MHz or 2.4 GHz. Different products which use the same frequency can sometimes be prone to interference with one another, degrading the performance of one or both systems.

RF LED products may be installed to provide control of an individual fixture, or of a group of fixtures wired together to a central control. The key benefit of using RF technology with LED products is to improve the ease of installation, ultimately providing greater cost savings and a better return on investment (ROI). Additional features, such as occupancy sensing, personal control, or daylight harvesting can be added to the system once the investment of RF transceivers is made for a lighting system. These features add value beyond just the initial energy savings from LED lighting and help improve the ROI.

Because lighting is a life safety system, selecting a robust RF protocol that is extremely reliable is essential. While interference may be annoying with cell phones, it is tolerable. Conversely, lighting that does not work reliably can be a major problem. While RF-enabled products are becoming much more common in the market, it is important to work with a manufacturer who offers a proven history with wireless control and a commitment to continued support, high performance, and innovation.

5.9 Product reliability and support for LED lighting systems

It is important when designing a lighting system to consider the installed lifetime of the system and all of its components. Nothing lasts forever (not even LEDs!), so designing and planning for system life can substantially mitigate risk, both to the performance of the system and the pocketbook of the owner. LED lighting is no different in this regard, and the rapid rate of adoption and growth may cause increased risk to all parties in the process, unless mitigated appropriately.

From initial design through eventual replacement, the specifier should consider the components (and subcomponents) of the system and how defective product and performance issues will be resolved. This is especially important for electrical sub-components like LED drivers, LED modules, and thermal devices (like heat sinks). Important questions to ask include:

- What are the terms of the product warranty?
- How long has the company been in business?
- What is the company's reputation in the market?
- Does the company support the products in the design (AND installation, AND maintenance) phases of the project?
- Who can the designer turn to with questions?
- Who can accommodate the changing products in the LED market?

Some specifiers “mock up” systems to understand exactly how the system will perform as close to its installed application as possible. It is useful to have the manufacturers of the components and subcomponents participate in the mock up with technical representatives to speak to the performance of their products and evaluate the intended operating conditions. Do the companies with critical components have technical staff to attend the mock up? Is the company sales representative knowledgeable and experienced? Who can the specifier and user turn to with questions?

When the system is initially installed, there is always the potential for mistakes and defects to occur. When this happens, knowledgeable and timely manufacturer response is critical to getting the system to work properly without delay. Consider a company that offers 24 hour technical and engineering support, with readily available field service. If a company does not have a technical representative available at any time to help with these issues, who will take responsibility? Often, the root cause of a poorly performing system (and an unhappy customer) is a problem which was evident at the initial design or installation. Who can the contractor and installer turn to with questions?

After the system is up and running, the long-term support of ALL the components becomes the critical point. What is the process to replace drivers when necessary? Who will provide them? How long will a company support obsolete products (1 year, 3 years, 5 years)? How will the driver, module, and fixture company make sure that replacement modules and drivers will work together? Who can the owner turn to with questions?

When the time comes to consider upgrading or replacing a system, which companies can be expected to come to the table? How can they help minimize waste? Who can help sustain a legacy system while a new system is being designed?

The answers to these questions should be clearly established at the outset of the project. Companies and products that have a comprehensive, positive response to all of them are the only practical choice.

6 Conclusion

Controlling LED lighting fixtures has become a major source of confusion, but also an excellent opportunity. The benefits of this new lighting technology are evidenced by the high rate of adoption by the industry and end-users alike, but using LEDs without care and attention to the necessary controls can ruin the experience.

LED fixtures and controls can use the same control technology, e.g.0-10 V, but that does not mean they will perform well together and provide reliable, smooth dimming performance. This is especially true with forward-phase and reverse-phase control, because they lack a formal standard. Even control technologies that follow a standard, e.g. 0-10 VDC, cannot promise a high performance standard; the standard only speaks to basic compatibility.

The only way to know for sure if a particular LED lamp or fixture will work with a particular dimmer is to test it. Whether that testing is a mock up or testing by the manufacturer, it is the only way to absolutely determine if flicker, pop-on, dead travel, etc. will occur. Also, keep in mind that you will not be able to visually determine all of the electrical characteristics of an LED product which affect performance or reliability, such as inrush current—you must find that out from the LED lamp or fixture manufacturer or limit the number you are using to avoid overloading the dimmer.

The Lutron LED Control Center of Excellence has tested hundreds of different fixture/driver/control combinations and posted the results online—an excellent resource in determining compatibility. All of these results are captured in the LED Product Selection Tool (www.lutron.com/LEDTool), which allows you to search by several different criteria to simplify product selection. However, a key factor in the world of LED lighting is the rate of change—LED modules are being updated every 6 months and that requires continuous new testing for controls compatibility.

Many manufacturers (both LED luminaire manufacturers and control manufacturers) conduct compatibility testing of their products. It has become an additional item on the designers to-do list to determine if the product testing has been done and if that manufacturer's assessment of "good dimming" will meet your customer's needs.

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