



*A NEMA Lighting Systems Division Document
LSD 49-2010*

Solid State Lighting for Incandescent Replacement— Best Practices for Dimming

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1 State of the Industry Today

1.1 Dimming in the Marketplace

Dimming of lamps has an important place in the lighting market. Of course, dimming saves energy; for every practical method of dimming, reducing the light level simultaneously reduces electrical power consumption. The use of light-emitting diodes¹ (LEDs) in general illumination can save additional energy from their very construction, compared to incandescent bulbs, because of inherently greater efficacy. Dimming LED lamps could save even more energy since their efficacy can actually increase, as compared with discharge or incandescent lighting sources, whose efficacy drops significantly with dimming.

In addition to energy savings, dimming changes the visual appearance of a space, thereby affecting the mood of the occupants. Customers value high performance dimming, and this white paper explores several elements to achieve high performance dimming. Today, customers pay a premium for LED products in general illumination. For applications where dimming is desired, these sometimes expensive LED products should offer high performance dimming characteristics. SSL products for general illumination are capable of high performance dimming, but only through careful explicit system design, as described in this paper.

1.2 Scope

This paper focuses on integrated LED lamps intended for replacement of general service incandescent lamps. Future white papers are planned to address other LED dimming topics, such as: color change; light output and efficiency (dimming curve); dimming protocols (Internet protocols, 0-10); LED modules with auxiliary drivers; and control architectures that dim without modulated power.

LEDs have become a popular light source because of their unique combination of characteristics: potential for excellent color rendering, energy efficiency, compact size, low voltage, and long life. Standards do not yet exist to guide the industry to develop consistent and cost-effective control of integrated LED lamps. Such standards will be required for widespread adoption. This paper provides a framework for discussing the issues and promotes the creation of an industry standard for LED dimming control.

The main objective for this paper is to encourage coordination among control, power supply, and LED module manufacturers to achieve desired performance. This effort may end up divided into (1) power supplies and integrated light sources designed for retrofit to existing incandescent dimmer sockets, and (2) power supplies and controls for new installations. The latter may achieve a simpler solution for the power supply if more intelligence is put into the control (dimmer). This must be coordinated within the industry; otherwise, there may be as many incompatible solutions as there are manufacturers, which will slow marketplace acceptance.

The large installed base of dimmer controls needs to be effectively included in any solution, so it is possible that more complexity must go into the power supply or integrated light source.

¹ The terms LED and solid state lighting (SSL) are used in this paper to mean an integrated LED lamp, following the definition in ANSI/IESNA RP-16-05 Addendum A.

1.3 Applications

The potential applications for LED lighting may be categorized as follows: retrofit, new construction, and new applications. In each category, LED lamps have the potential to offer significant advantages.

By far, the largest potential residential application for integrated LED lamps is as a replacement for general service incandescent lamps (retrofit). A 2002 U.S. study² estimated there were over 4 billion incandescent lamps in use. The number of installed Edison base sockets suitable for replacement lamps will remain large for some time. Although consumers are shifting from incandescent lamps to self-ballasted compact fluorescent lamps³, integrated LED lamps do have a market opportunity. To effectively compete for this market opportunity, the LED lighting industry must take into consideration the entire ancillary benefits of LED lamps, such as maintenance, light quality, etc.

There are approximately 150 million dimmers installed residentially⁴ that are rated for use with line-voltage incandescent or halogen lamps. Thus, integrated LED lamps intended to replace general service incandescent lamps will almost certainly be operated with incandescent dimmers in many installations.

New construction and innovative applications are being developed more rapidly than ever before. The guidance provided in this paper will help these future applications succeed where dimming is required or desired.

1.4 Audience

The intended audiences for this paper fall into two broad market segments: commercial and residential.

In the commercial market segment, lighting designers and contractors seek information on applications, both for dimming options that exist today and those under development. Manufacturers of LED power supplies and controls seek technical information to assist new product development and support.

In the residential market segment, sales personnel from retail stores and residential customer dealers desire to learn specific points about dimming integrated LED lamps.

In both of these market segments, consumers and electricians want to become familiar with their options.

2 LED Dimming Performance

To introduce the technical descriptions of LED power supplies and controls later in the paper, we first identify performance expectations customers have from the perspectives of aesthetics, energy savings, and reliability.

² Navigant, U.S. Lighting Market Characterization, Sept. 2002, p. xiii

³ NEMA publishes sales indices of incandescent and fluorescent lamps. For example, see <http://www.nema.org/media/pr/20090512c.cfm>

⁴ Independent estimate

2.1 Aesthetic Performance

Many of the aesthetic expectations consumers have regarding high performance dimming derive from their experience with incandescent lamps. Accordingly, the following qualitative characteristics of incandescent lamps should be taken into account in assessing the level of dimming performance in an integrated LED lamp:

- **Dimming range.** Lamps dim to a very low light level, practically off, compared to the maximum light level. This range is often expressed as a percentage of the full output level.⁵
- **Smooth changes.** Light level changes are smooth, and the light levels of adjacent lamps closely track each other while adjusting the level in either direction over the full dimming range.
- **Starting and warm-up.** Lamps turn on at the minimum light level setting. Light level reaches the desired level very quickly.
- **Stable light level.** The light level does not change spontaneously; there are no flicker or shimmer effects.
- **Noise.** The lamp, power supply, and control combination is practically inaudible over the entire range of light levels.
- **Control Flexibility.** Motion controls/occupancy sensors, photoelectric eyes, etc., can control the lamp.
- **Color change.** In the case of incandescent sources, the color temperature is related to the physical temperature of the tungsten filament. The color temperature of incandescent lamps decreases with light level: thus a color shift from blue to orange is expected as the light level is reduced.

2.2 Energy Savings Performance

LED lamps are more efficacious⁶ than incandescent lamps. Specifically, they produce more visible light, measured in lumens, for each watt of power they consume. So a fundamental measure of LED lamp performance is the lumens-per-watt (LPW) efficacy at full light output.

LED lamps can actually exhibit higher efficacy as they are dimmed because of reduced thermal loads and semiconductor processes. Incandescent and halogen source efficacy drops markedly as they are dimmed. For example, a 50% reduction in power reduces the light output of incandescent lamps by a factor of four. Similarly for a CFL, a 50% reduction in power reduces the light output by about two thirds.

⁵ As light level reduces, the pupil of the eye dilates. Thus the perceived light level does not drop as fast as the measured light level. When expressed as percentage of maximum light level, the perceived light is approximately the square root of the measured light. For example, dimming until the measured light level is 10% of the maximum would result in perceived light level 30% of the maximum. See S.S. Stevens. On the psychophysical law. *Psych. Rev.*, 64(3):153–181, May 1957.

⁶ Luminous efficacy expressed in lumens per watt is equal to the light output, measured in lumens, divided by the input power, measured in watts.

A high performance LED lamp dimming system maximizes system efficacy during typical dimming operation. While LED lamps and/or power supplies may be optimized when they produce a single level of light output, electronics for dimming typically require some compromises. LED lighting systems with dimmers will save energy because they can be set to select the minimal light output necessary for visual comfort. While system level LPW values may vary over the dimming range, the overall energy consumption is reduced in approximate proportionality to the light level. LED power supplies typically consume some overhead power that is not transferred to the lamp even at the lowest light levels, so the lowest system LPW will occur when dimmed to the lowest level. Table 1 below gives a numeric example to illustrate this effect on system efficacy.

Table 1
Example of LED Dimming System Performance

Parameter	Units	Value
Total power at full output	W	10
Power supply overhead at full output	W	1.5
LED power at full output	W	8.5
Lumens at full output	lum	600
System efficacy at full output	lum/W	60
LED efficacy at full output	lum/W	70.6
Maximum dimming level	-	10%
Total power at max dim	W	1.17
Power supply overhead at max dim	W	1
LED power at max dim	W	0.17
Lumens at maximum dimming level	lum	60
System efficacy at max dim	lum/W	51.3
LED efficacy at maximum dimming	lum/W	352.9
Increase in LED efficiency at maximum dimming level	-	400%

In addition to dimming, advanced lighting control systems save additional energy by turning on the LED lamps only when they are needed, for example based on time of day, natural light level, or whether the space is occupied. In combination with other sensing and control devices, dimming control systems can save a significant amount of energy beyond the direct comparison savings of the energized light sources.

2.3 Reliability Performance

The life expectancy of most conventional light sources increases when dimmed. Dimming reduces the lamp power and system heat load, thus a beneficial effect on the source life is realized. LED lamps similarly benefit from dimming. Table 2 lists typical light source lifetimes. Rated life for most sources is defined as the time interval to 50% lamp operational failures⁷, whereas the rated life of systems with LED sources is commonly defined as the time interval to 50% lumen depreciation failures, when only 70% of the initial light output of the LED lamp

⁷ When tested under standardized measurement conditions. See IESNA documents: LM-40-01 (fluorescent); LM-47-01 (HID); LM-49-01 (incandescent); LM-65-01 (CFL)

remains. This paper uses these definitions in lieu of standardized reliability measures for LED systems⁸.

Table 2
Typical Lifetime of Light Sources, at Full Light Output and when Dimmed

Light Source	Typical Life at Full Light (h)	Typical Life when Dimmed (h)
Incandescent	750–1500	1500–6000
Halogen	3000–5000	3000–20000
CFL, non-dim	6000–8000	N/A
CFL, dimmable	8000–10000	derated
Fluorescent	15000–40000	no change
LED, non-dim	20000–50000	N/A
LED, dimmable	20000–50000	higher

Temperature has an important impact on electronic lifetime. Electronic devices last longer if they operate at cooler temperatures. Compact fluorescent lamps (CFL), and often LED systems, have power supply electronics integrated with the light sources, so the reliability of the electronic circuit directly impacts the lifetime of the package. In other words, the integrated LED lamp life will be no longer than the shortest component life in the system. In addition, lower junction temperatures under dimmed operation results in better lumen maintenance for LED devices, which further extends their expected life.

3 Existing Control Types

Existing dimming controls can be divided into two broad categories: incandescent phase-cut dimmers and fluorescent controls. The division is more conceptual than practical, as some fluorescent ballasts respond to a phase-cut signal, and there exist some LED power supplies that respond to control types originally intended for fluorescent ballasts. This paper addresses applications using phase-cut dimmers typically used with incandescent lamps.

3.1 Incandescent Phase-Cut Dimmers

The phase-cut dimmer was developed for incandescent lamps. One of the advantages of phase-cut dimmers is that a standard switched lighting circuit may be easily retrofitted with existing wiring by merely changing the conventional two-way switch to a dimmer control. In a standard installation, current that is conveyed through wires to the lamp powers the light fixture. In a simple switched lighting circuit, a switch in the “on” position will allow the current to pass unmodified through the switch to the lighting fixture. The switch in the “on” position allows the fixture to use electricity all the time. Figure 1 shows this concept.

⁸ Global standards under development have generally adopted this definition for LED light sources. They will become formalized with the publication of completed consensus industry standards.

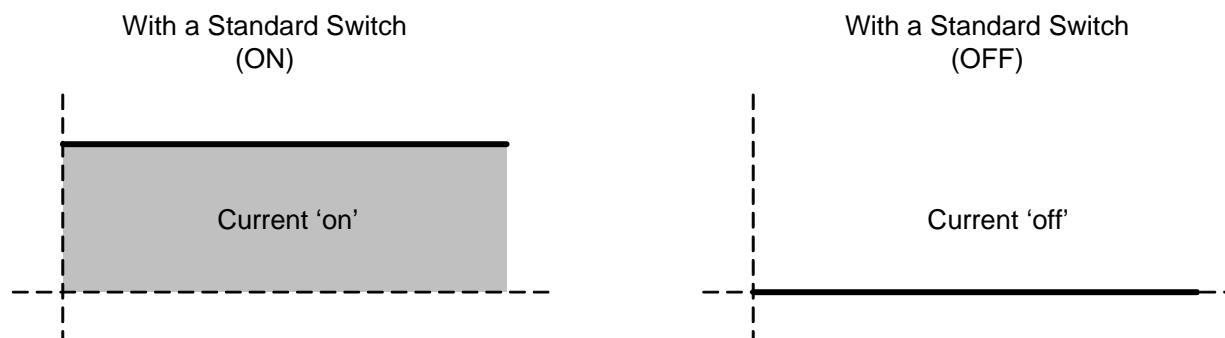


Figure 1
Basic Operation of a Switch to Control a Lamp

A phase-cut dimmer is a unique kind of switch that uses a special circuit to “turn on and off” the current supply to the fixture at regular intervals, typically 120 times per second. This is fast enough that the human eye does not perceive any interruption, in the same way that celluloid movies look continuous even though they are actually a series of static images shown in very quick succession.⁹

The amount of time the current is “on” determines how bright or dim the lamp will be. For each “on/off” cycle (1/120th of a second), the more time current is “on,” the brighter the lamps will be and the more energy used. This is shown in Figure 2.

In the United States, power is delivered from the electric utility as a sinusoidal voltage, with a root mean square (rms)¹⁰ value of 120 volts and repeating 60 cycles per second (see Figure 3). A phase-cut dimmer contains a thyristor semiconductor device (triac, field effect transistor, or silicon controlled rectifier) that acts like a switch. When the thyristor turns “on,” current flows through the circuit; when the switch turns “off,” no current flows through the circuit. By turning the switch “on” and “off” twice every line cycle, the rms voltage applied to the lamp is reduced from 120 volts to a lower value, so the rms current that flows is also reduced. As the rms current flowing through the lamp is reduced, it dissipates less power, and so produces less light.

⁹ IEEE PAR 1789 is looking at the flicker issue, and because LEDs can be modulated so quickly, there are indications that 120 Hz is indeed observable—there is no thermal lag or phosphor inertia.

¹⁰ Mathematically, the root mean square (rms) of a periodic waveform is found by squaring the value, averaging over an integer number of periods, and taking the square root. Conceptually, it is related to the magnitude of a waveform. For a pure sine wave, the rms value is 0.707 times the amplitude.

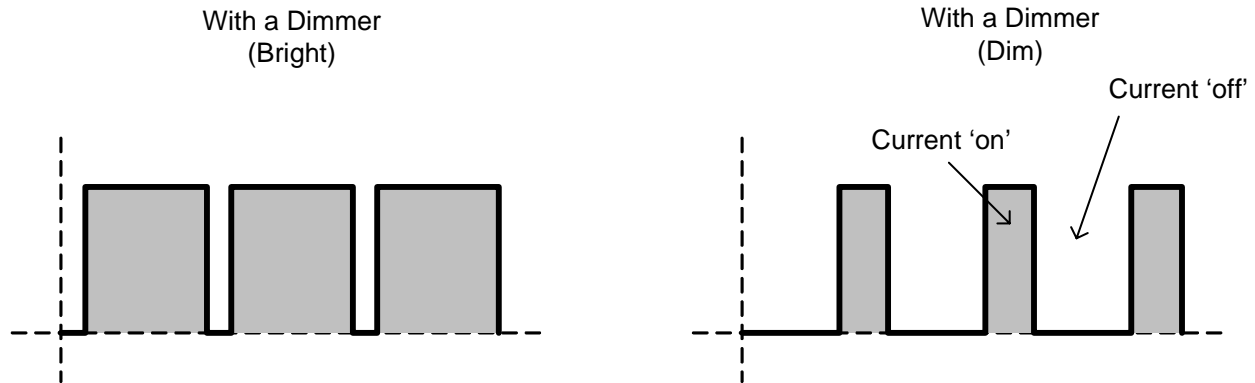


Figure 2
Basic Operation of a Dimmer to Control a Lamp

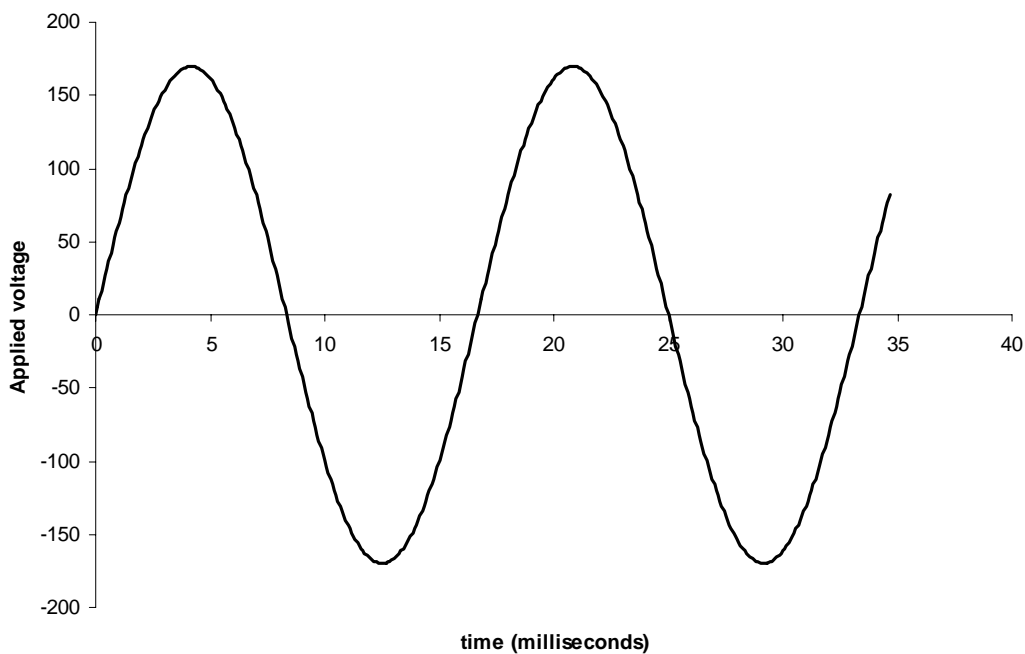


Figure 3
Typical Sinusoidal Line Voltage Supplied from Utilities in the United States: 60 cycles per second, 120 volts rms. This voltage is applied to the lamp when a switch is "on."

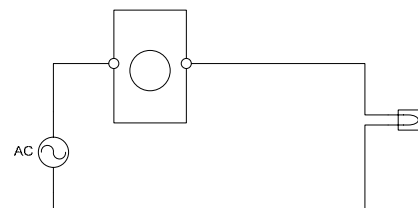
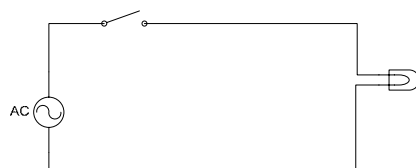
Phase-cut dimmers are classified according to the types of load they dim: line-voltage incandescent and halogen, or low-voltage halogen. Low-voltage halogen lamps require the line voltage amplitude to be transformed to a lower voltage. This is done with either a magnetic or an electronic transformer. Circuit diagrams of switched and dimmed incandescent loads are shown in Figure 4.

INCANDESCENT
OR HALOGEN
LOAD TYPE

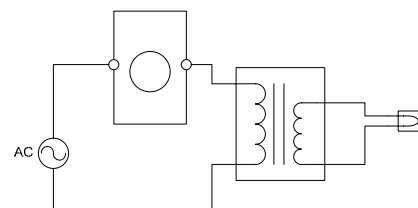
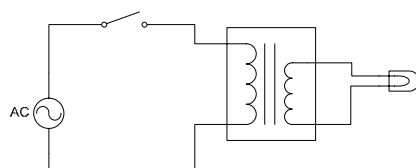
SWITCHED

DIMMED

LINE VOLTAGE



LOW VOLTAGE
(MAGNETIC
TRANSFORMER)



LOW VOLTAGE
(ELECTRONIC
TRANSFORMER)

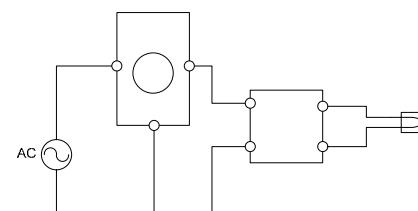
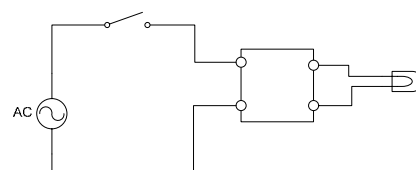


Figure 4

Circuit Diagrams of Switched and Dimmed Line-Voltage and Low-Voltage Incandescent/Halogen Loads

3.1.1 Leading Edge Phase-Cut Dimmers

The “leading edge” phase-cut dimmer (also known as forward phase) is one of the most popular types installed, because of its simple design. The semiconductor switch is usually a triac, which turns itself “off” (unlatches) every half-cycle when the line voltage (and therefore the current through the triac) passes through zero. The triac is turned “on” every half-cycle by a simple timing circuit. Adjusting the timing of when the triac turns “on” dims the lamp (see Figure 5, parts a and b).

Leading edge phase-cut dimmers are used with incandescent lamps and line-voltage halogen lamps. Special leading edge phase-cut dimmers can be used with magnetic step-down transformers to dim low-voltage halogen lamps. Dimmers designed for magnetic step-down transformers carefully balance the current in the positive and negative half-cycles, to avoid saturating and overheating the transformer.

Dimmer circuits that use a triac require a minimum load, typically in the range 5W to 40W with a 120 V_{rms} line, to keep the triac “on” (latched). This minimum load requirement is not always satisfied by many LED systems in deep dimming operation. Caution should be taken to determine if phase-cut dimmer circuits are properly loaded when installing integrated LED lamps to replace incandescent or halogen lamps.

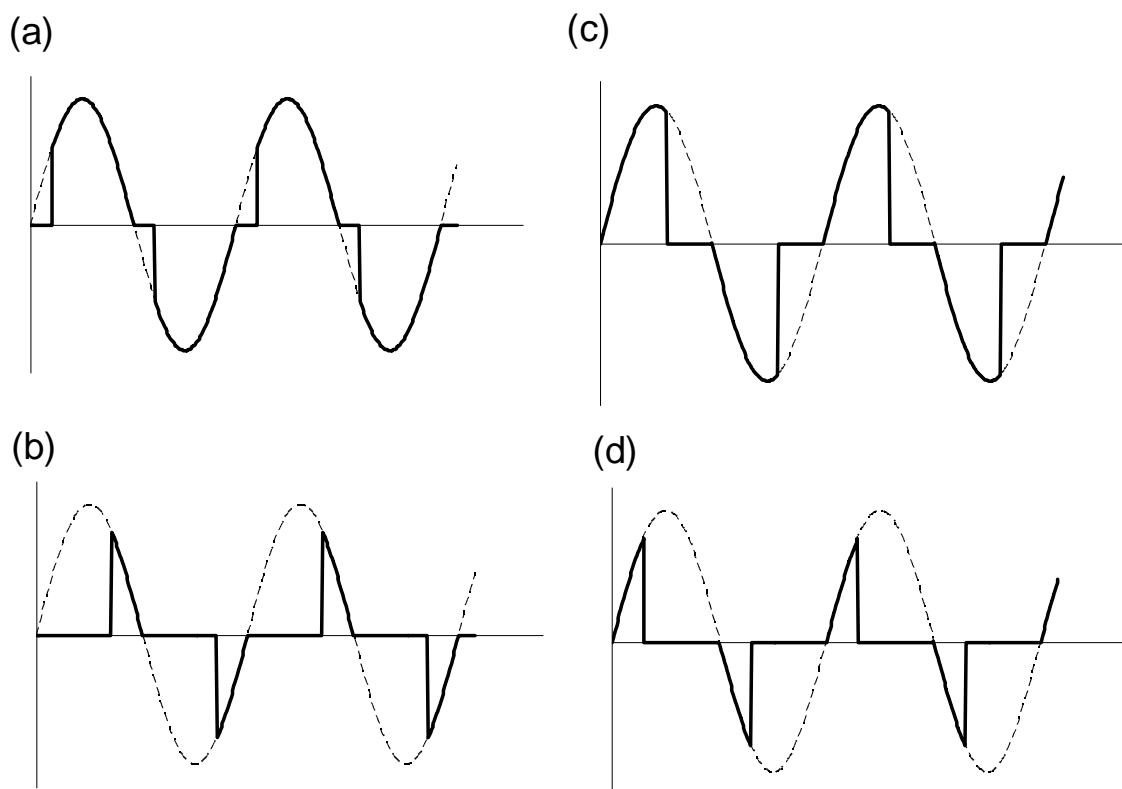


Figure 5
Example Voltage Waveforms Applied to the Lamp from Phase-Cut Dimmers:
 (a) leading edge, high light level;
 (b) leading edge, low light level;
 (c) trailing edge, high light level;
 (d) trailing edge, low light level.

Dashed line represents uncut line voltage, what would be applied if the switch were “on.”

3.1.2 Trailing Edge Phase-Cut Dimmers

The “trailing edge” phase-cut dimmer (also known as reverse phase) is popular for use with electronic transformers to dim low-voltage halogen lamps. Trailing edge means that the voltage turn-off is abrupt, but the voltage turn-on is gradual. Gradual voltage turn-on avoids high inrush current when the capacitors in the electronic transformer charge up. The semiconductor switch in a trailing edge phase-cut dimmer is typically a field-effect transistor (FET), which is turned “on” and “off” with timing circuitry (see Figure 5, parts c and d).

4 LED Drivers

The driver is a critical element in a successful LED product. It manipulates the LED current and facilitates user control. It must have a rated life comparable to the LED array (20,000–50,000 hours). For most LED systems, the driver performs a number of additional functions, including power factor correction and voltage isolation. The driver also receives control signals for dimming.

4.1 LED Drivers as Power Supply

This primary function of the LED driver is to supply the current that is appropriate for the individual LED dies. LED dies, like all diodes, pass current in only one direction, called the forward bias. A diode will not pass current or emit light (in the case of LED) when reverse biased. An individual LED die requires a minimum voltage from its anode to cathode (the “forward voltage”) of a few volts in order to pass current. The relationship between voltage and current is similar to other diodes, in that a small change in forward voltage may result in a large change in current. Since electrical power from the utilities is delivered as 120 V_{rms} ac, practical LED power supplies perform a power conversion from ac to dc and step-down the voltage to match the forward voltage of the LED dies¹¹. Figure 6 shows the electrical symbols for a generic diode and for a light-emitting diode. Figure 7 shows the current-voltage characteristic for a diode, and the light output as a function of LED current.

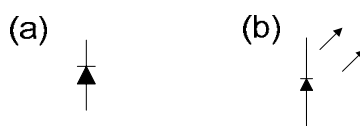


Figure 6
Electrical Symbols for (a) Generic Diode and (b) Light-Emitting Diode

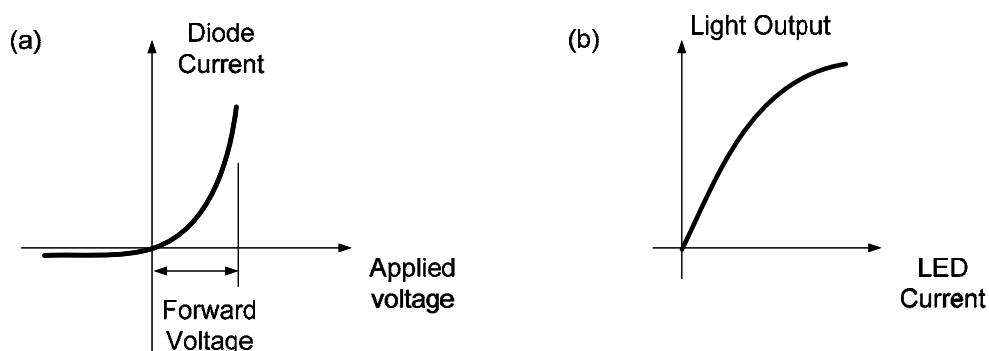


Figure 7
Comparison of Diode Current-Voltage Characteristics
(a) Current-voltage characteristic for a diode;
(b) Light output versus current for a light-emitting diode (approximately linear)

4.2 Driver Types

There are two basic types of LED drivers: constant current and constant voltage. The type of LED driver that is required depends on whether the individual LED devices are connected directly to the driver or if they have additional current control means for individual die or series strings of die. A constant current driver is a regulated current supply. It provides a regulated current, and allows the output voltage to adjust. In contrast, a constant voltage driver is a regulated voltage supply. It provides a regulated voltage, regardless of the current drawn by the

¹¹ Line-voltage integrated LED lamps exist but have constraints regarding transients and overall dimming capabilities and special care is needed in dealing with the implementation of these devices.

load. Given the highly non-linear voltage-to-current relationship in LEDs, constant voltage supplies generally should only be used when some additional current controlling means is used to limit dissipation in individual dies.

For a number of individual LED dies connected electrically in series (as might be done to make a string of lights for a cove application), the current passed through them is the same for each diode, and the sum of the forward voltages of the individual LED dies is the voltage requirement for the array. A constant current driver connected to the series array is sufficient for a successful electrical design.

For more than one series string of LED dies connected in parallel (a series/parallel combination, see Figure 8, part c), the situation becomes more complex. Each series string is intended to be operated by a constant current source; two series strings will not necessarily have the same forward voltage drop. And yet due to the series strings wired in parallel, each string has the same applied voltage and the current is shared between the strings. Thus, if one series die string has a forward voltage that is significantly lower than another, the string with the lower voltage will take a larger share (or all) of the current, causing an imbalance in light from the different strings. Furthermore, the dies in the lower voltage string will get hotter than the others, causing a further drop in forward voltage and possible thermal runaway. Thus, it is very important that each LED die string operate at its design current, and that the total current required by the combination of die strings is equal to the regulated current provided by the driver. The LED array design must take into account these electrical properties of dies. Certain techniques such as the use current limiting resistors, cross connections, and current mirrors can help balance the current.

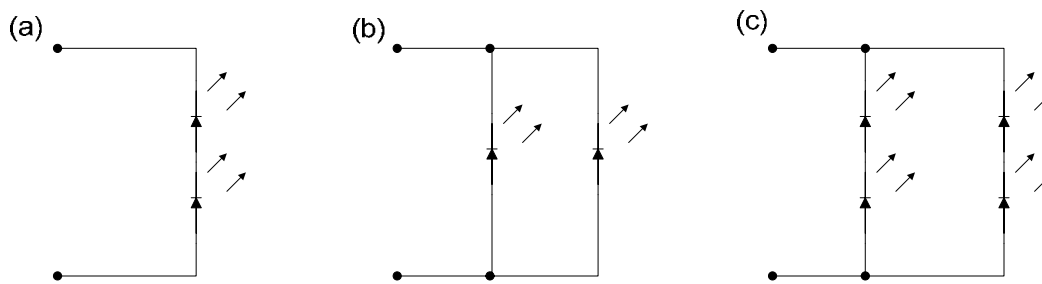


Figure 8
Example LED Wiring Configurations
(a) Two LED dies wired in series. The same current flows through each diode so forward voltages add
(b) Two LED dies wired in parallel. The same voltage is applied to each diode so current is shared
(c) Two series chains wired in parallel

4.3 Efficiency

Today's LED drivers are designed for multiple applications on different loads, and provide many critical features such as circuit isolation, current regulation, and wide input voltage range. Each of these features affects the driver's efficiency.

An LED driver designed to operate at a single LED current can be very simple and efficient, since it can be optimized. An LED driver intended for dimming operation must be designed to

produce a range of LED current, and therefore the design requires compromises. Dimmable LED drivers require circuitry to interpret a control signal. The additional control circuitry and broader current range that deliver significant energy savings usually result in lower driver efficiency.

4.4 Current Regulation

The LED driver must regulate the current through the load. This can be done in many ways, depending on the application. However, they all depend on passing current through some impedance that has a resistive component. The resistance causes loss in the circuit in proportion to the current. Hence, higher current drivers will typically be less efficient than lower current drivers, although good design can minimize the difference.

4.5 Input Voltage Range

Many drivers are designed for installation in a broad range of applications and products. Since line voltages used for lighting range (typically) from 120 V to 277 V in the U.S., from 120 V to 347 V in Canada, and from 110 V to 220 V in Mexico, products must have circuits in them to meet power quality and industry standard specifications. These requirements usually require a compromise between efficiency and performance.

4.6 Power Quality

There are many important electrical specifications that a driver must meet for installation in a building or home. These may include power factor, total harmonic distortion (THD), inrush current, and radiated and conducted electromagnetic interference (EMI)¹².

An incandescent lamp is a purely resistive element, and draws current that is in phase with the ac line voltage. Electronic gear, like an LED driver, contains reactive circuit elements that cause the current drawn from the line to be out of phase with the line, causing slight power line losses. Power factor is a measure of this reactive load component. The power factor scale ranges from zero (purely reactive loads) to unity (purely resistive loads). Utilities prefer products to have a power factor as close to unity as possible to minimize resistive power line energy losses.

Typical LED drivers contain at least one switching power supply. The high-frequency current drawn by these power supplies causes harmonic distortion of the current drawn from the line. This can result in neutral wire heating, and load imbalance in three-phase systems, as well as other challenges. For example, standards exist for high frequency fluorescent lamp ballasts that limit the total harmonic distortion.¹³ Products should contain adequate filtering to meet this specification in an actual application.

Electronic gear, which contains large input capacitance, may draw a large “inrush” current when power is first applied, or even during each line half-cycle, if operated from a phase-control (incandescent) dimmer. This inrush current can stress circuit breakers, switches, and dimmers, if it is significantly higher than the peak line current¹⁴.

¹² In the U.S., FCC part 15.

¹³ ANSI C82.11-2002, Table 3

¹⁴ See NEMA 410 for inrush requirements.

4.7 Drivers with Incandescent Dimmers

Despite the fact that LEDs are still being studied and their applications are still in development there are many consumers interested in using integrated LED lamps in home applications even this early in the development cycle of the technology. In many cases, these homes already have incandescent dimmers (or entire lighting systems) installed. Ideally, residential products have LED drivers that are compatible with the large number of phase-cut incandescent dimmers already installed. In practice, this compatibility is not always achieved.

Incandescent dimmers have many requirements, which are met by most incandescent lamps (such as constant leakage current path, minimum load, resistive impedance characteristic), but which are critical to the operation of the dimmer. If an LED driver does not meet these requirements, the LED array controlled by the driver may flash, flicker, not turn on, or operationally fail.

Performance standards for dimmable retrofit LED drivers must include an electrical description (a specification) of the dimmer to ensure compatibility with the installed base of incandescent dimmers.

5 Dimming Compatibility Issues

Bearing in mind the characteristics of dimming and LED technologies described above, several areas for evaluating the compatibility of LED systems and dimming controllers are identified. While the specific criteria for acceptability vary from application to application, the basic issues may be generalized across applications. For example, acceptable dimming compatibility for a daylight harvesting system in a commercial environment may not be useful in a residential application, such as a media room. Accordingly, specific recommendations on acceptable objective criteria for evaluating dimming compatibility are beyond the scope of this document. Below are questions and concerns that should be addressed to determine if a dimming control and an LED system are compatible.

5.1 Full on Light Output

- a. What is the reduction in light output when the dimming control is full on?

5.2 Maximum Dimming Level

- a. What is the maximum dimming level of the luminaire?

5.3 Dimmer Control Travel and Light Output Profile

- a. Over what amount of travel of the dimmer control does the LED product dim?
- b. Where would the light level plateau and remain at a low level before turning completely off?
- c. Is the relationship between dimmer control position, which determines the rms voltage (phase angle, on-time, duty cycle, etc.), and light output known?

5.4 Maximum Number of Units/Minimum Load

- a. Are there a maximum number of LED lamps on a dimmer control to achieve reliable results?

- b. On an incandescent dimmer rated for a certain power watts at a certain rms volts line voltage, the maximum load is determined by the current draw, given by Table 3. Is the load from LED lamps kept less than this value, to avoid compromising the reliability of the dimmer?

5.5 Inrush Current

- a. On an incandescent dimmer, the maximum inrush current is determined by the characteristics of cold tungsten. See Table 3. Is the load from LED lamp inrush current kept less than this value, to avoid compromising the reliability of the dimmer?

5.6 Repetitive Peak Voltage

- a. Incandescent dimmers typically employ semiconductor devices that can withstand only certain voltages. Is the repetitive peak voltage resulting from the combination of incandescent dimmer and LED load kept under this value, to avoid compromising the reliability of the dimmer?

5.7 Minimum Number of Units/Minimum Load

- a. Are there a minimum number of LED lamps on a dimmer control to achieve reliable results?
- b. On incandescent dimmers with triac semiconductors (the most common type of incandescent dimmer), the minimum load is determined by the triac holding current. From the component data sheets, typical values are found in Table 3. Does the LED lamp draw this minimum current?

5.8 Low End Turn On

- a. Does the LED product turn on at all dimming levels of the dimming control?

5.9 Cut Out

In some cases, when the dimming level of the dimmer is changed from the full on to full dim, the LED product may turn off at some point during that transition but before full dim of the dimmer is reached.

- a. Does the LED product turn off or “cut out” during the travel of the dimmer?

5.10 Turn On Time

- a. What is the maximum turn on delay for an LED product?
- b. Where in the dimming range does this delay occur?
- c. Does the turn on delay vary with dimming level?
- d. Does the variability in delay between multiple LED products connected to a single dimmer exhibit an objectionable visual artifact or “popcorn” effect?

5.11 Flicker

- a. Is there any noticeable flicker when the LED product is dimmed?
- b. Is there any noticeable stroboscopic effect when the LED product is dimmed?

5.12 Color Shift

- a. Is there any color shift when the LED product is dimmed?
- b. If so, what is the color shift?

5.13 Audible Noise

- a. Is there any audible noise from the dimmer control of the LED product when dimming?
- b. Are there any specific conditions when audible noise occurs (e.g., minimum or maximum number of products on a single dimmer control)?

5.14 Dimmer Reliability

Dimmers designed and rated for use with incandescent loads must satisfy several parameters:

- a. Capability of the air-gap switch (make & break arc energy)
- b. I^2t rating of the main semiconductor which passes load current or safe-operating-area
- c. I^2t rating of the PCB traces
- d. Peak current and voltage stresses on any RFI component
- e. Continuous power dissipation of resistive elements (PCB, chokes, FETs)
- f. Continuous power dissipation of voltage-based semiconductors (triacs, IGBTs, diodes)

These parameters are typically exercised during safety standards testing, including:

- a. Overload cycling (1.5x the rated current for 100 cycles)
- b. Endurance cycling (rated load with inrush for 10,000 cycles)
- c. Heat run (temperature test) at rated load current and line voltage
- d. dc output (inductive loads only)
- e. Air-gap switch test (100 cycles with semiconductor shorted)

In the case of self-ballasted LED systems intended for general service incandescent lamp replacement, the installed base of incandescent dimmers is the most likely control to be encountered. The relevant characteristics of the installed base of incandescent dimmers can be determined easily by measurement on incandescent loads, and approximate values are summarized in Table 3.

Because of the confusion in the marketplace regarding substitution of non-incandescent lamps for incandescent lamps (for example, "23W = 100W", meaning that the lumen output of a 23W CFL is comparable to the lumen output of a 100W incandescent lamp), a dimmer may be operated with a load that exceeds the one of the criteria above, which in turn compromises dimmer reliability.

To summarize: the incandescent lamp dimmer reliability is ensured if each of the stresses when the dimmer drives non-incandescent loads is less than the stress when the dimmer drives the rated incandescent load.

Table 3
Summary of Stresses that can Damage Incandescent (Inc.) Dimmers and Self-Ballasted LED Lamps, and Characteristics of Installed Base of Incandescent Dimmers that can Affect Compatibility Behavior

Parameter	Stress from interaction could damage dimmer	Stress from interaction could damage self-ballasted LED lamp	Interaction could result in poor performance	600 W Inc. Dimmer (typical)	1000 W Inc. Dimmer (typical)
Inrush current (A)	X			78	116
Continuous operating current (A rms)	X			5	8.3
Current crest factor (*)	X			3	3
Allowable pass-through current in off state (mA)			X	1	1
Compliance to low-voltage standards (0–10 V products)					
LEDi response to dimming					
Leading-edge voltage ring-up (V)	X			200	200
Trailing-edge voltage ring-up (V)	X			200	200
Leading-edge current ring-up (A)	X			9	15
Trailing-edge current ring-up (A)	X			9	15
Max VA delivered / switched VA (%)		X		120	120
Max rms current delivered vs switched rms current (%)		X		110	110
Response to asymmetry (Vdc)		X		2	2
high end: light at 120 Vrms vs switched light (%)			X	95	95
Voltage when dimming control is at the maximum light level setting (Vrms for 120 VAC line)			X	108	108
Voltage when dimming control is at the minimum light level setting, triac latched (Vrms for 120 VAC line)			X	<30	<30
Voltage when triac pops on (Vrms for 120 VAC line)			X	65	65
Voltage when triac drops out (Vrms for 120 VAC line)			X	10	10
Triac latching current, upper limit (mA instantaneous)			X	100	120
Triac holding current, upper limit (mA instantaneous)			X	50	75
Triac repetitive peak off-state current at 100°C— I_{drm} (mA) for dimmers with electronic off (service switch in normal ON position).			X	3	3
Max off state pass-through current (mA), for night light (analog dimmers).			X	5	5
Max off state pass-through current (mA), for dimmer power supply (digital dimmers).			X	20	20

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