A NEMA Lighting Systems Division Document
LSD 73-2015

Energy Savings with Fluorescent and LED Dimming

Prepared by:

NEMA Ballast and Lighting Controls sections
National Electrical Manufacturers Association
1300 North 17th Street, Suite 900
Rosslyn, Virginia 22209

Approved: June 18, 2015
Published: July 14, 2015

www.nema.org

The opinions expressed in this statement represent the consensus views of the member companies of the Lighting Systems Division of the National Electrical Manufacturers Association. The members of the Lighting Systems Division manufacture traditional technology lamps and ballasts, light-emitting diodes (LEDs and OLEDs), LED lamps and modules, LED drivers and power supplies, luminaires, lighting controls, and management systems.

Contents

1 Scope

The scope of this paper includes dimmable fluorescent ballast and Light Emitting Diode (LED) drivers that are controlled by 0-10 V (1-10 V) control input. This paper explains the relationship between the control input voltage and overall energy consumed by these ballasts and drivers.

2 Purpose

Dimmable fluorescent ballasts and LED drivers consume less power when dimming. However, determining the energy savings at different output levels can be challenging because several components comprise lighting systems: control, control wiring, power source, and light source. This paper describes the signal path from the user control input through the control wiring, ballast or driver, and lamp or LED module. It also explains factors that affect energy consumption and savings, efficacy, and user experience at each stage. This paper is written for stakeholders interested in energy-efficient lighting, including manufacturers, specifiers, facility managers, and consultants.

3 References

ANSI C82.11-2011, *American National Standard for Lamp Ballast: High Frequency Fluorescent Lamp Ballast*

ANSI C82.13-2002, *American National Standard for Lamp Ballasts—Definitions for Fluorescent Lamps and Ballasts*

IEC 60929, Edition 4.0, *AC- and/or DC-supplied electronic control gear for tubular fluorescent lamps—Performance requirements*

NEMA LL 9-2011, *Dimming of T8 Fluorescent Lighting Systems*

4 Definitions

All definitions in this white paper are consistent with the definitions provided in ANSI standards. Refer to ANSI C82.13.

5 0-10 V Dimming

5.1 BACKGROUND

For close to 30 years, general lighting control by DC voltage has been used throughout the US to control brightness of fluorescent lighting. Called 0-10 V dimming in the US, in other parts of the world it is referred to as 1-10 V dimming. It is used today to control light sources such as LEDs. Throughout this paper, references to ballasts also include drivers for LEDs or other sources.

The ANSI standard is C82.11-2011, *American National Standard for Lamp Ballast: High Frequency Fluorescent Lamp Ballast,* Annex A, and the IEC standard is IEC 60929, *AC- and/or DC-supplied electronic control gear for tubular fluorescent lamps—Performance requirements,* Appendix E2. Both standards are similar and define a minimal set of requirements:

Current is always sourced at the ballast (10μA to 2mA). This allows very simple devices, such as potentiometers, to control dimming. Note that most modern control devices are capable of sourcing current; in general lighting, however, the ballast is always the source. (0-10 V is different for theatrical lighting and generally not compatible).

The only requirement for control signal voltage in ANSI C82.11 is value of lamp power:

1 V = minimum value of lamp power

1 V to 10 V = lamp power rising from minimum to maximum value
0 V to 11 V = stable lamp operation
0 V to 1 V = minimum light output

Included in the standard is a requirement for an overall voltage limit of ± 15 VDC, as well as polarity protection.

5.2 0-10 V VARIATION

The 0-10 V dimming method is not precise and is prone to differences in control voltage versus light output for various reasons:

a) The standards referenced above loosely define the requirements for this control method; however, they do not specify the actual operation of the light source over the range of voltage. As a result, ballasts and drivers have various dimming curves (brightness versus control voltage), such as Linear, Square Law, Logarithmic, and many variations. Since the ballast determines the dimming curve, controls generally focus on linear control voltage output versus the control position.
b) The current is sourced by the ballast or driver, meaning that the more ballasts or drivers connected in a circuit, the more current and voltage difference between control and ballast.
c) The wiring practice is not specified and varies greatly. The size and length of wire will make a great difference. For example:

    1) Control set to min (1 V)
    2) 1000 ft 20 AWG wire (2 wires = ~20 ohms)
    3) 25 ballasts = .05A control current (at min setting)
    4) Voltage difference between control and ballast = 1 V
    5) Voltage at ballast = 2 V

    This voltage drop is worst at the lower settings.

Because of differences in control voltage versus light output, many types of ballast flatten the top and bottom of the dimming curve to make reaching minimum and maximum brightness possible with most controls. Many controls also allow trimming minimum and maximum settings. For example, a particular ballast might reach full brightness at 8.5 V and minimum brightness at 2.5 V.

This flattening is not usually a problem for the user, since the brightness is normally adjusted to the desired level by operating the control and observing the lighting. The user is generally unaware of control voltage variations.

5.3 CONCLUSION

Many factors affect the accuracy of brightness and energy use in response to the control voltage. Consequently, control voltage should not be used for determining energy use unless it has been calibrated for a specific installation. Since energy use is directly related to light output level, the relationship of light output versus power input should be the primary method to accurately determine lighting system energy consumption.

6 Dimming Fluorescent Systems

6.1 CONTROL AND DIMMING LINEARITY

All fluorescent dimming systems are inherently energy saving. The ability to lower a light level brings an associated reduction in energy consumption. It is important to consider that not all ballasts are as efficient during dimming or respond to the 0-10 VDC control signal in the same way. The difference in control response is less noticeable when all ballasts in a site are the same model by the same manufacturer. The light level, in most applications, is set via a monitor photocell that looks for a specific amount of light on a scene. This is common in “big box” retail and other stores that use sky lighting and daylight harvesting.

With respect to the 0-10 VDC control input, some ballasts have a nonlinear response curve that has larger dead zone areas where the ballast does not respond linearly to a change in the control voltage. The ideal ballast will have a dead zone between 0 and 1 VDC, then respond linearly from full dim at 1 VDC, to the maximum output at 9 VDC, and having a top-end dead zone between 9 and 10 VDC. While the control is between 1 and 9 VDC, the response of the ballast should be linear.

In Figure 1, the pink and blue traces represent the dimming input response to the 0-10 V input control voltage for two different manufacturers’ dimming ballasts. The blue trace seems to exhibit a larger dead band at the upper end, staying constant output from 0 V through 8 V, then starts to linearly dim as the control voltage is reduced. For this ballast, the user can adjust the control downward but not see or measure any reduction in light or energy level for some portion of the control rotation.

The pink trace shows an abbreviated dead zone from 10 VDC to about 9.5 VDC, where the output is constant. Once decreased below the 9 VDC area, the dimming is linear. In this case, if the customer adjusts the dimming control down, a light level and energy level reduction occur in the first few degrees of control rotation. The preferred case is to have a dimming ballast that closely responds to the established ANSI dimming control characterization found in ANSI C82.11-2011. That way, every change of the dimming control will translate into a linear light level and energy level reduction.

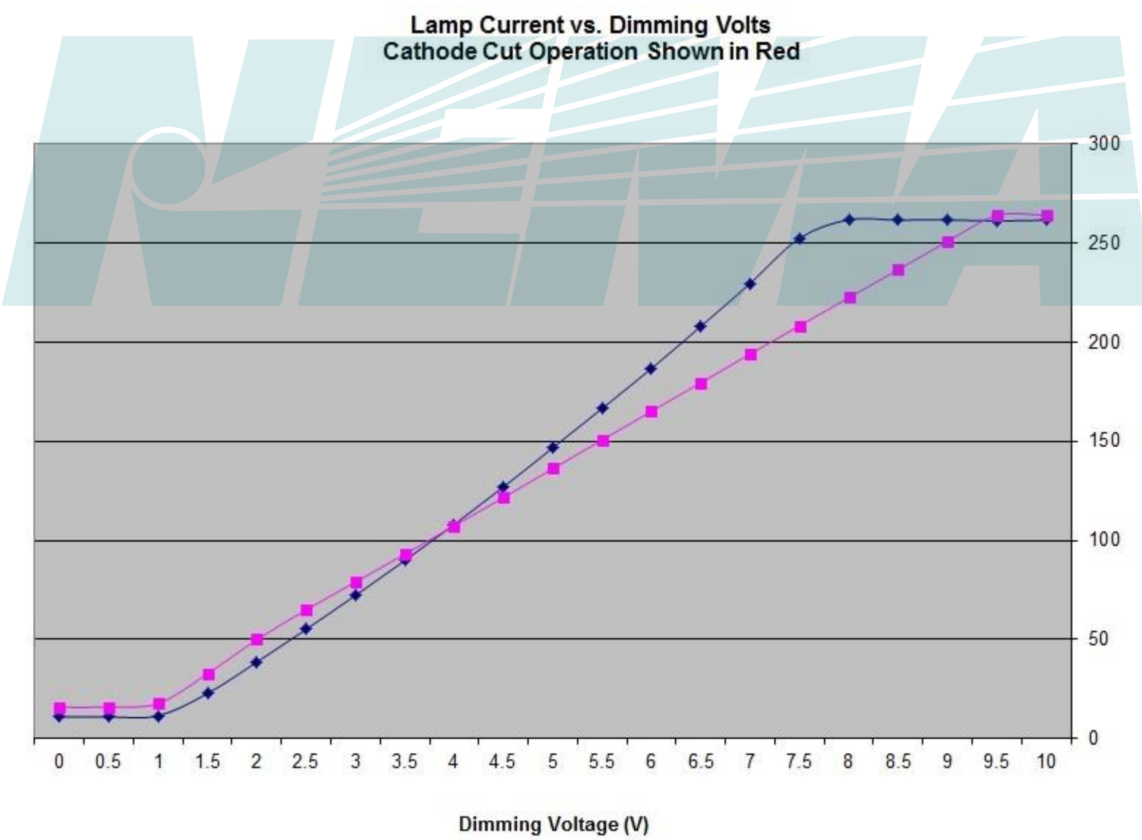

Figure 1
Lamp Current versus Dimming Volts

6.2 CONTROL AND INPUT WATTAGE LINEARITY

The previous case showed the relationship between control voltage and lamp current or light output. Figure 2 shows the relationship between control voltage and input power for the same two ballasts as seen in Figure 1. Pink and blue represent the same ballasts in Figure 1.

Similar to the blue trace in Figure 1, there seems to be an extra dead zone in the dimming response of the blue ballast. The input wattage stays at maximum until the control voltage is reduced to below 8 VDC when the ballast begins its dimming action and is linear with dimming voltage to down to 1 VDC per the ANSI-defined dead zone. Lack of response at the high end can cause the user to turn the dimming control knob and not see any reduction of light or energy for many degrees of rotation of the control. While this ballast still saves energy, the user becomes concerned about the reduced dimming range of the control, since some of the rotation has no visible effect.

The pink trace shows dimming results as the dimming voltage comes below 9 VDC, giving linear dimming performance. As the dimming level is reduced, around 6 VDC, a bump in the wattage curve is noticeable where the wattage slightly increases, then begins to fall again as the control voltage is reduced. The ballast with the pink trace employs cathode cut-off circuitry, where the cathode heating is turned on only for deep dimming, as defined by NEMA LL 9. At discharge currents greater than ~155mA, no additional cathode heating is required to keep the lamp cathodes in thermionic emission. When the ballast is asked to deliver discharge current greater than 155mA, the ballast will switch the cathode heating off, resulting in energy savings, since no energy is wasted to heat cathodes that are already warm from the arc discharge. This can be seen in Figure 2 in the range of about 9 to 6 VDC, where the input wattage for the pink ballast is considerably lower than that that for the blue ballast. In the blue ballast, cathode heating is applied for the entire dimming cycle and does not have a cathode cut-off characteristic. The pink ballast will turn the cathode heat on and off as needed, in response to the control voltage and the discharge current. As mentioned earlier, the trip point is about 155mA. Below 155mA, cathode heating is on; above 155mA, cathode heating is off.

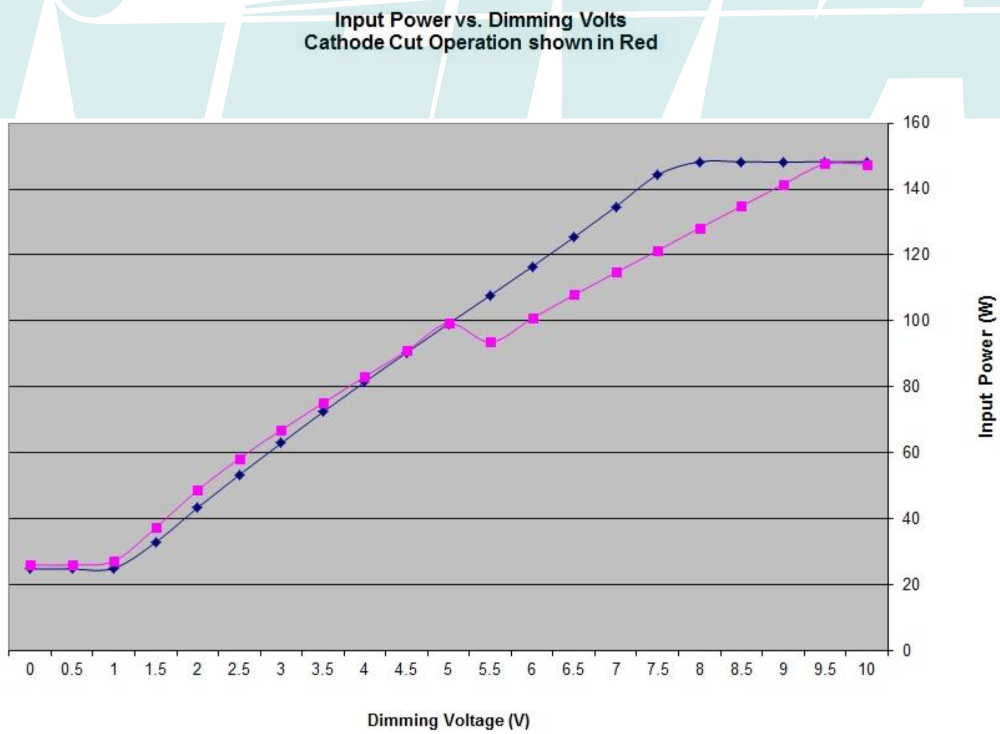

Figure 2
Input Power versus Dimming Volts

6.3 NEMA LL 9 COMPATIBILITY

Figure 3, from NEMA LL 9, defines the need for cathode heat during deep dim operation. LL 9 was developed to define how much cathode heating was required at various points during the dimming curve. Ballasts that are compliant with NEMA LL 9 will help the lamp maintain a full lamp life rating and minimize early failures due to end darkening and cathode depletion.

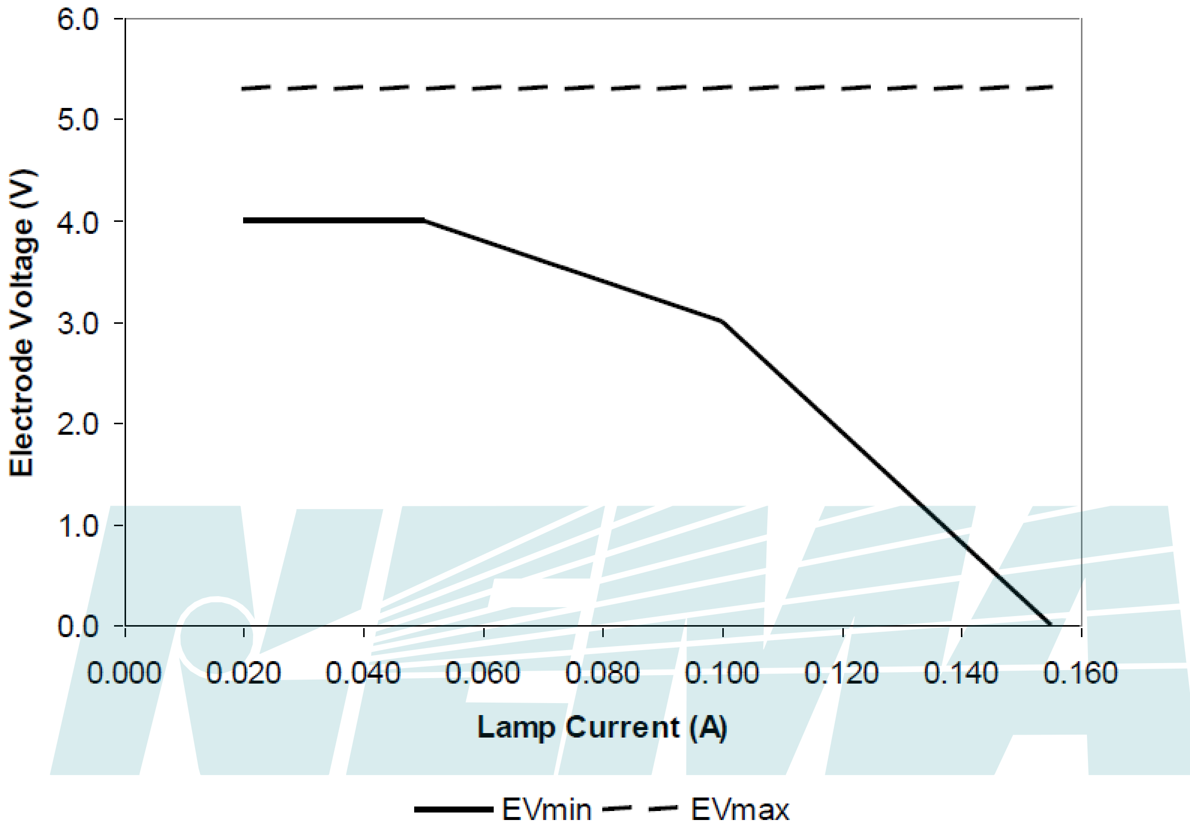

Figure 3
Cathode Heat Requirements for Deep Dim Operation

The measured cathode heating voltages for each lamp should be within the limits shown in order to be compliant with NEMA LL 9. Examples of compliant and noncompliant ballasts follow.

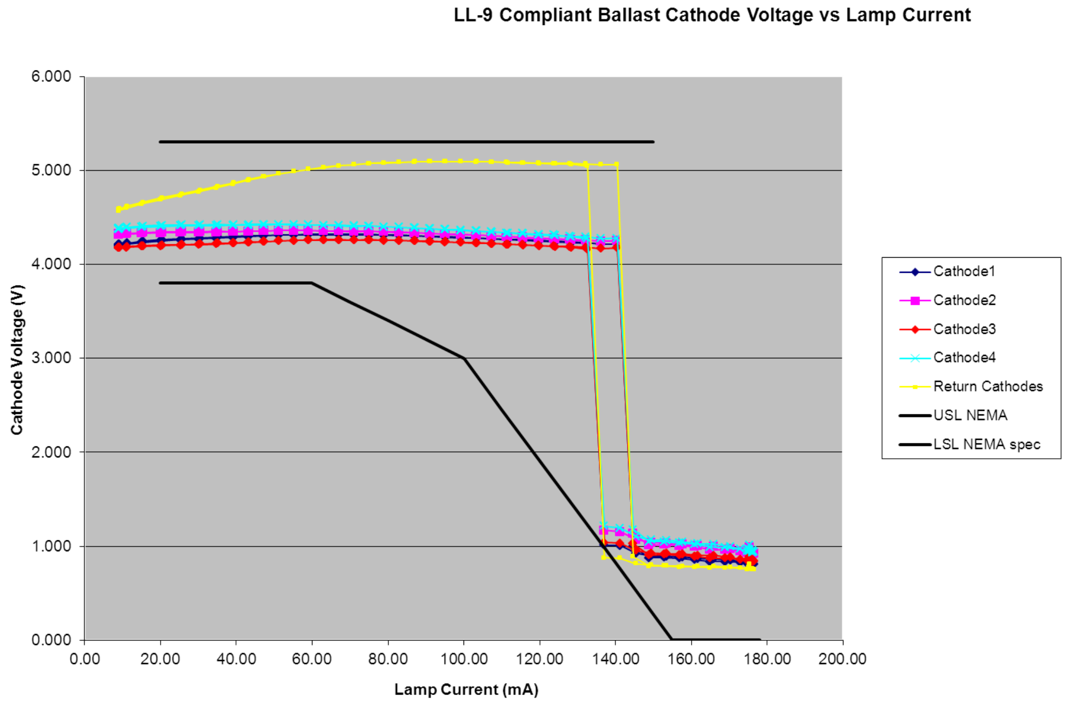

Figure 4
NEMA LL 9–compliant Ballast Cathode Voltage versus Lamp Current

Figure 4 shows a ballast that is NEMA LL 9–compliant in terms of cathode heating voltage supplied versus lamp discharge current. At currents above 160 mA, no additional heating is required. Below 160 mA, the heating voltages should be within the limit lines to ensure sufficient heating, but not so much heating that the emission mix boils off the cathode.

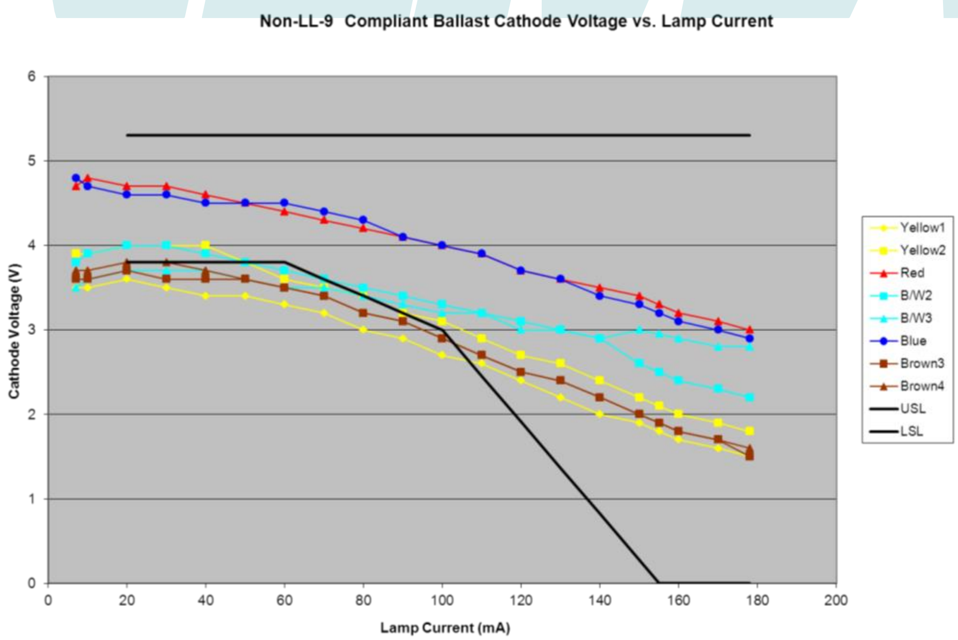

Figure 5
Non-NEMA LL 9–compliant Ballast Cathode Voltage versus Lamp Current

Figure 5 shows a ballast that is not compliant with NEMA LL 9. In this example, some of the voltages on the respective lamp leads are not sufficient to ensure proper cathode heating, since some traces fall below the defined lower limits. If the lamp cathode is not sufficiently heated during deep dimming, then it is possible the cathode will not be as emissive as it should be, and cathode sputtering will occur. Sputtering will prematurely deplete the emission mix, leading to excessive end darkening and shortened lamp life.

In conclusion, the dimming ballast needs to perform several functions to satisfy the user in terms of visible light delivered, energy savings, and lamp life. To ensure ballasts are properly evaluated, refer to ANSI C82.11 for control voltage linearity and characteristics, and to NEMA LL 9 for the relationships of cathode heating voltage versus discharge current. The ballast should be compliant with both standards and follow the characteristic examples shown in this paper.

7 Dimming LED Systems

7.1 LED DRIVERS OPERATION

LED drivers are different from fluorescent ballasts. Fluorescent ballasts provide an alternating current, whereas LED drivers provide a DC or an interrupted DC output. Fluorescent ballast can be reduced as an abstraction to a constant current source. The lamp voltage is established by the lamp operation as a response to the lamp provided by the ballast. There are two major LED driver types: constant current and constant voltage. LED drivers can operate a wide range of loads. See figures 6 and 7.

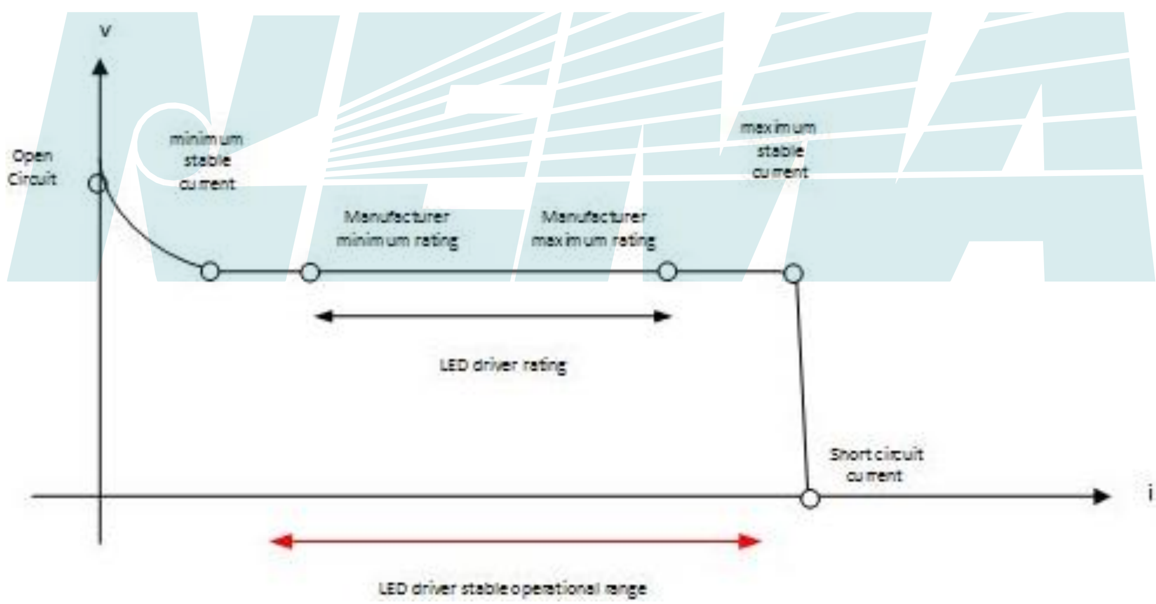

Figure 6
LED Driver, Constant Voltage Type

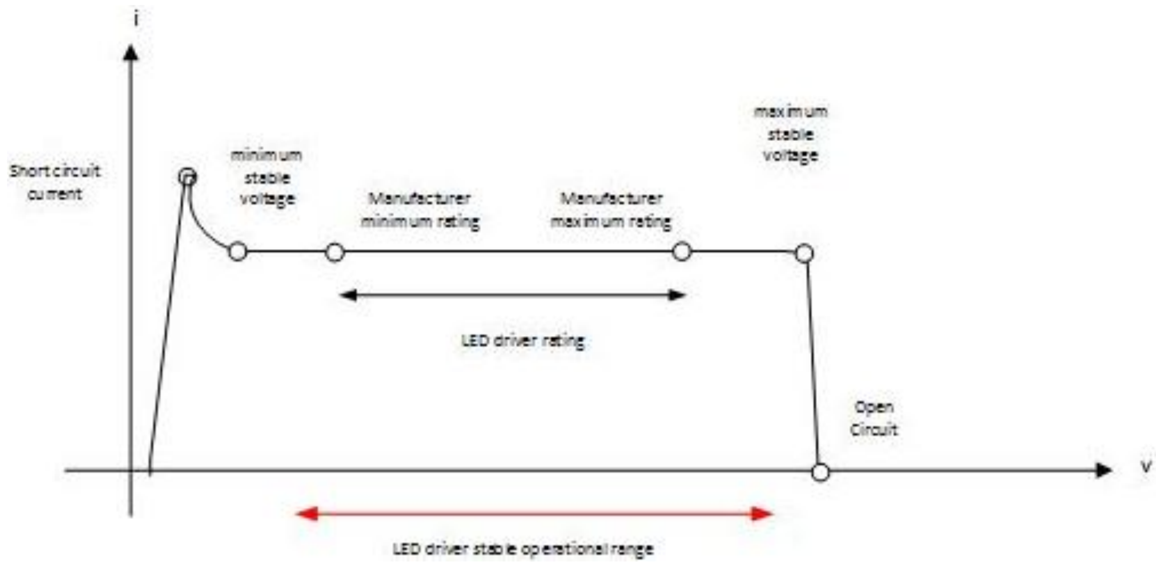

Figure 7
LED Driver, Constant Current Type

The LED driver flexible operation capability is typically communicated in terms of an operating window (see Figure 8).

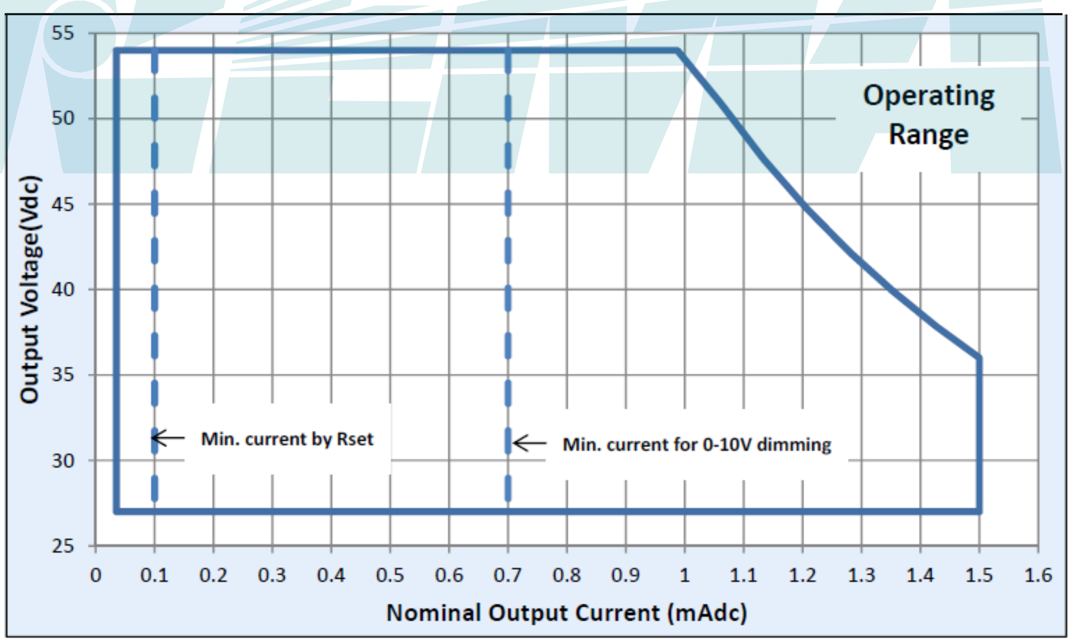

Figure 8
LED Driver Operating Range

7.2 LED DRIVERS DIMMING OPERATION

LED drivers can have a dimming interface. One commonly used in LED applications is similar to the 0-10 V dimming interface used in electronic ballasts (ANSI C82.11-2011) (see clause 5.1). While there are other dimming interfaces, such as phase cut dimmers or DALI, this paper focuses on the 0-10 V dimming interface. The LED driver output can be controlled by the end user by means of applying a 0-10 V signal to the dimming interface port (see Figure 9).

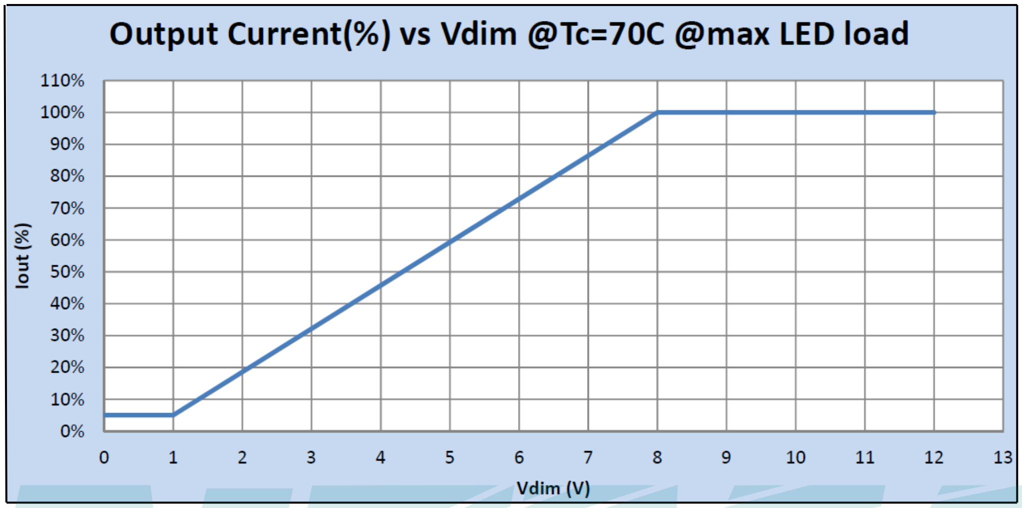

Figure 9
LED Drivers 0-10 V Dimming

Typically, the 0-10 V dimming interface self-consumes a limited amount of energy to operate. It requires current in the hundreds of µA. The LED driver input power decreases as the output power decreases, leading to energy savings (see Figure 10).

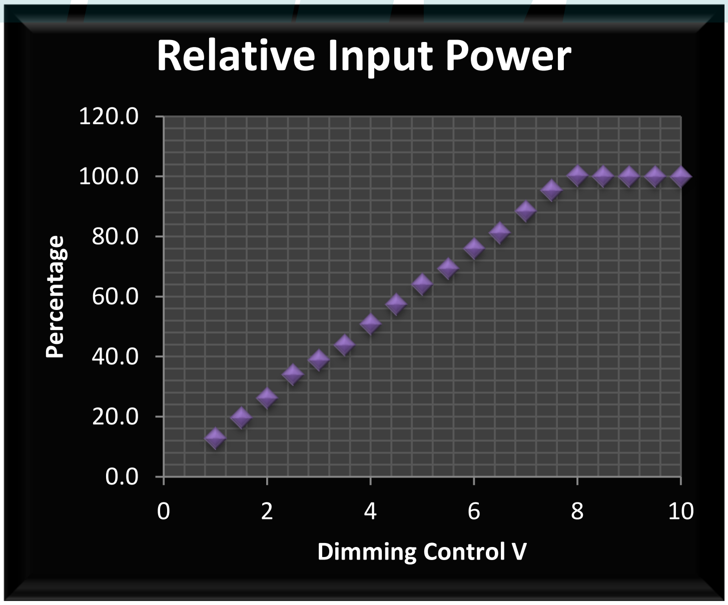

Figure 10
LED Driver Input Power as a Function of the Dimming Control Voltage

7.3 LED LUMINAIRE DIMMING EFFICIENCY AND LIGHT OUTPUT

Figure 11 describes the LED luminaire light output relationship with input power. It shows the reduction in lumens is fairly linear with the reduction of luminaire input power. At 50% of initial lumens, the input power is at 45% of its initial value, showing that system efficacy increased slightly during a portion of the dimming operating range. At the 20% lumen level, the power is also at 20%.

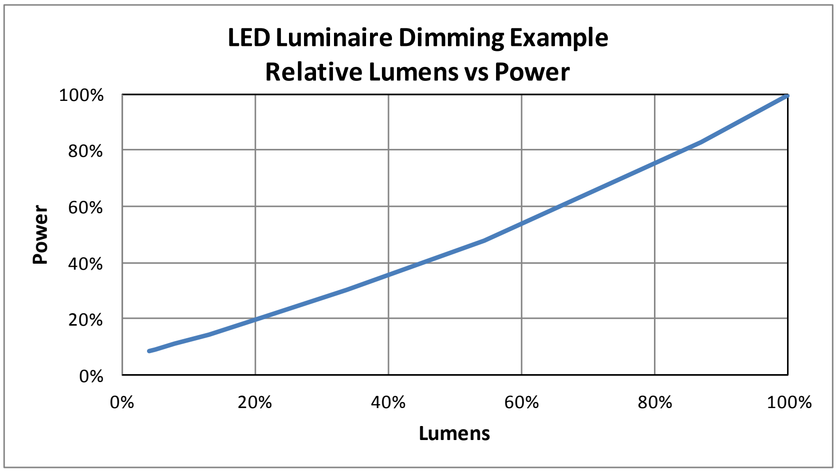

Figure 11
LED Luminaire Dimming Example
Relative Lumens versus Power

Figure 12 describes the variance of LED luminaire efficacy with dimming operation. The figure indicates that system efficacy initially increases when dimming due to the LEDs operating more efficiently at lower driver currents. In the deep dimming mode, driver efficiency drops more significantly and overall system efficacy lowers. System efficacy will vary based on many factors, including module efficacy, driver efficiency, luminaire optical efficiency, LED operating current, thermal management, and ambient temperature.

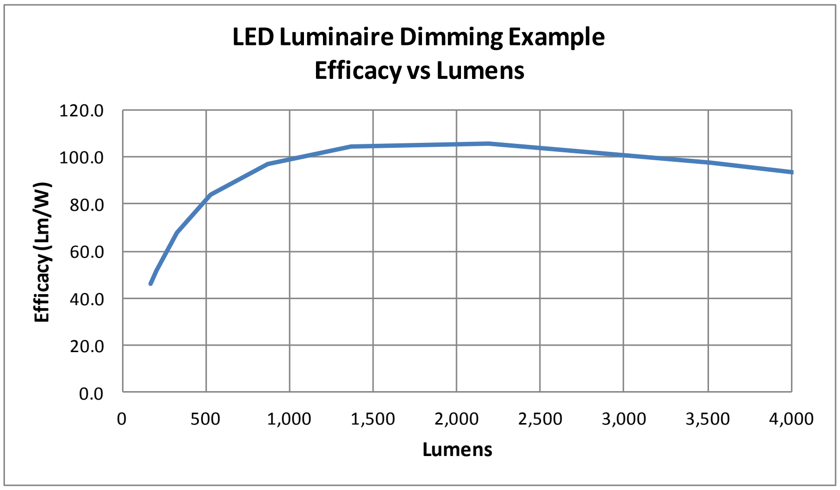

Figure 12
LED Luminaire Dimming Example
Efficacy versus Lumens

7.4 DIMMING LED SYSTEMS CONCLUSIONS

Dimming LED systems leads to input power reduction. LED driver efficiency reduces slightly in deep dimming conditions (see Figure 13). LED driver total efficiency varies slightly, typically efficiency reduces about 1-2% in the full dimming range, whereas LED luminaire efficacy may increase at first and reduce in deep dimming conditions (less than 10% of the initial light output). Power quality (measured in terms of power factor and harmonic content) might reduce in deep dimming conditions. However, the benefits achieved by the end user, utilities, and building owners, in terms of energy consumption, are maximized by adding dimming to their lighting systems.

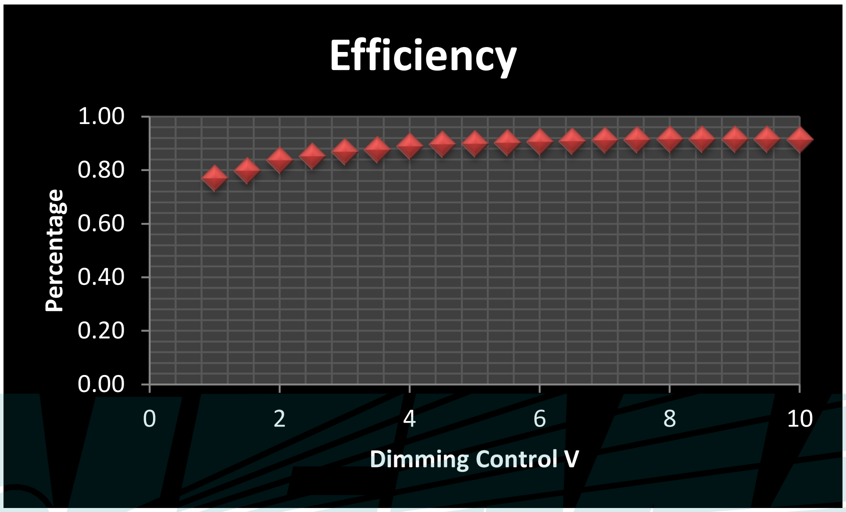

Figure 13
LED Driver Efficiency as a Function of the Dimming Control Voltage

8 Conclusions

Dimming always saves energy.

Even though there is not always a linear relationship between light output and energy consumed, and efficacy varies with light level, *in modern systems, there is always a reduction in energy when lighting is dimmed.*

Even though a fluorescent dimming curve might have a discontinuity due to cathode cutout, the energy saved is still significant with dimming ballasts. There is no reason not to use these products.

An anomaly that has been noted in the past is a blip in the dimming curve for some fluorescent lamps. The blip is caused by cathode cutout, as explained in section 6.2. Cathode cutout is important to dimmable lamps because it allows the lamp to be dimmed even further than typical lamps can be. This allows for additional energy savings, as well as improved lighting control for some applications. While the blip appears to show an increase in power requirements, it occurs well below the full power output, so energy is still being saved with this type of ballast over a non-dimmed system, while providing additional features and longer life for the lamp.

The perceived brightness does not decrease as quickly as the power decreases when dimming. Therefore, the benefit is greater that might be assumed.

Perception of brightness can be described by Stevens' Power Law. This is often expressed as a square law (*IES Handbook,* 9th Edition) or cube law (*IES Handbook,* 10th Edition). For example, the square law

says that a reduction in perceived brightness to half its max level is caused by reducing the actual light output (and, approximately, the driver power output) to one quarter its max level.
This means that reduction in power through dimming can be much greater than the reduction in perceived brightness.

There is not always a linear relationship between the control voltage and the amount of energy being saved.

Variations are common in 0-10 V signaling, so it is important not to rely on the control voltage as a single reference to determine energy consumption. Lighting is usually adjusted by users based on light level, and many controls can compensate for the DC voltage variation. Light output versus energy should be the primary reference when comparing energy used. Always consult the ballast, driver, lamp, or luminaire manufacturer's data to determine how much energy will be consumed for a given light level.

LEDs can be more efficacious when dimmed.

Because of lower die temperatures, LEDs can have a higher efficacy at lower portions of the dimming curve.

§