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BUREAU OF INDIAN STANDARDS
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Draft National Lighting Code of India

Part 3 Electric Light Sources and Their Accessories
Section 1 Solid State Lighting (LED Technology)

(First Revision of SP 72 (Part 3 / Section 1)

Illumination Engineering and Luminaries Sectional Committee, ETD 49	Last Date for Comments: 02-03-2025

FOREWORD

(Formal clauses of the draft will be added later)

In recent decades, the evolution of light sources for general illumination has undergone rapid advancement, particularly with the emergence of solid-state technology. Since 2016, the widespread adoption of LED applications has surged, displacing traditional low-pressure and high-pressure discharge lamps to a significant extent. With LED poised as the primary light source forthe future, and given the swift pace of technological development, this chapter focuses primarily on the intricacies and advancements within LED technology.

A snapshot of traditional lighting, including its major applicable specifications, is provided for quick reference to users, facilitating comparison and potential usage scenarios if needed.

This code introduces the Solid-State Lighting (SSL) technology mainly for Light Emitting Diodes (LED).

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PART 3 ELECTRIC LIGHT SOURCES AND THEIR ACCESSORIES
SECTION 1 SOLID STATE LIGHTING (LED TECHNOLOGY)

(First Revision)

1 SCOPE

This section of the code (Part 3/ Sec 1) covers crucial information necessary to comprehend the typical characteristics of the LED technology for better understanding of LED while manufacturing, user application as well for the specifier community. Although there are concise descriptions of the different construction and performance characteristics of LED technology but the designer should also consult the catalogues /data sheet of individual manufacturers for additional information.

2 REFERENCES

The following Indian standards are necessary adjunct to this section of the code.

IS No/ Other Standard	*Title*
IS 418: 2005	Tungsten filament general services electric lamps
IS 2418 (Part 1):1977	Tubular fluorescent lamps for general lighting services Part 1 Requirements and tests
IS 9900 (Part 1):1981	High pressure mercury vapour lamps Part 1Requirements and test
IS 9974 (Part 1): 1981	High pressure sodium vapour lamps Part 1 General requirements and test
IS 12948: 1990	Tungsten halogen lamps (non vehicle)
IS 15111 (Part 2): 2002	Self-ballasted lamps, Part 2 Performance requirements
UL 13	Power- Limited circuit cables —Types and applications

3 TERMINOLOGY

The definitions of the terms used in this section a are given Part 1 of this code.

4 CLASSIFICATION OF LAMPS

4.1 General

The electric light sources technology can be classified according to their primary operating principle (*see* Fig. 1).

a) *Incandescent lamps* — These emit light through a heated metal filament. The halogen lamp contains a special vapour that enhances its effectiveness. Due to their low effectiveness, these types will be phased out in the future;

b) *Gas discharge lamps* — The light from these lamps is produced by a discharge between two electrodes in a glass or ceramic tube fil LED with a gas. There are two ranges based on the most significant gas: sodium or mercury. High or low pressure in the glass tube can subdivide either of these ranges; and

c) *LEDs* — LEDs are semiconductor devices. When a current flow through an LED, electrons combine with electron holes, releasing energy as light. In the process, "extra" energy is released as light. Using a variety of semiconductor materials and manufacturing processes, the light's wavelength (and consequently its colour) can be altered to suit. In addition, the wavelength spread of the emitted light is comparatively narrow, resulting in colours that are pure (or saturated).

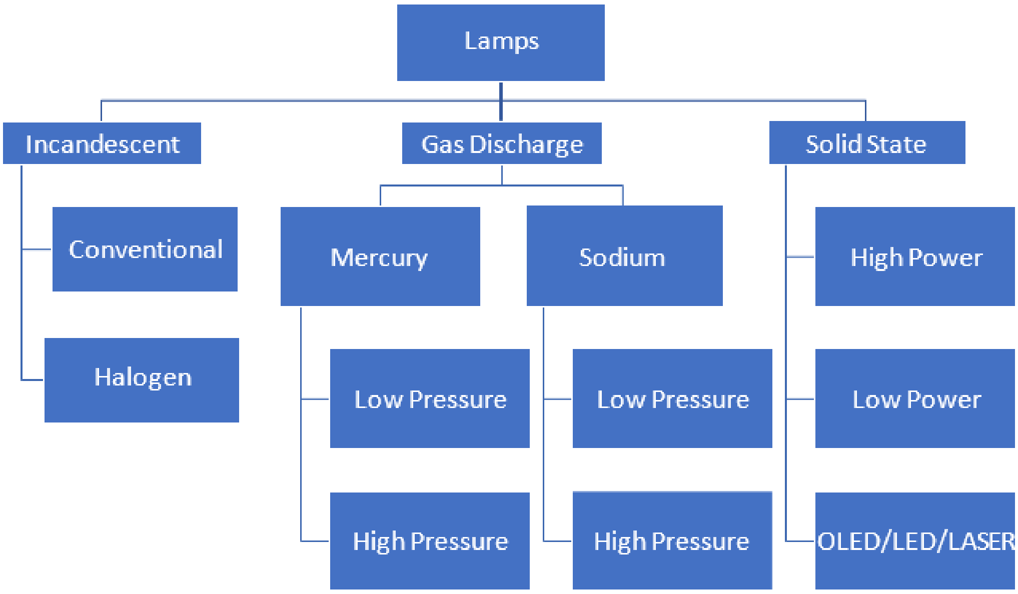


Fig. 1 Broad Classification of Lamps

Table 1 shows the broad characteristics of different light sources. This enables the user and specifier to select the right combination. It is obvious that LED light sources are winning the selection criteria in most applications of general lighting. Hereafter this chapter is dedicated for LED technology with respect to light source. Table 2 shows characteristics /specification for incandescent, low pressure and high pressure and induction lamps.

Table 1 Characteristics of Different Light Sources

(*Clause* 4.1)

Sl No. (1)	**Light Source** (2)	**Wattage Range** (W) (3)	**Efficacy** (lm/W) (4)	**Life** (h) (5)	**Lumen. Maintenance** (percent) (6)	**Starting Time** (sec) (7)	**Colour Rendition** (Ra) (8)	**Dimming Capability** (9)	**Colour Temp** (K) (10)
i)	Incandescent	15 to 150	8-to 12	500 to 1,000	50 to 65	Instant	100 Excellent	Excellent	2700
ii)	Low voltage halogen	1 to 30	12 to 20	1000 to 2,000	50 to 75	Instant	100 Excellent	Excellent	2700 to 3000
iii)	Mains voltage halogen	300 to1500	20 to 27	200 to 2,000	50 to 60	Instant	100 Excellent	Excellent	3000
iv)	Fluorescent T8 and T8 tri- phosphor	18 to 80	60 to 90	5,000 to 15,000	60 to 85	3 to 10	60 to 88	Possible	2700 to 6500
v)	Fluorescent T5	14 to 58	80 to 105	10,000 to 20,000	80 to 90	3 to 10	80 to 98	Possible	2300 to 6500
vi)	Compact fluorescent integral (retrofit)	5 to 180	60 to 85	5,000 to 15,000	65 to 85	2 to 5	65 to 85	Very Low	2300 to 6500
vii)	Compact fluorescent non-integral (2 pin and 4 pin)	5 to 120	60 to 85	5,000 to 20,000	65 to 85	2 to 5	70 to 90	Possible	2300 to 6500
viii)	Blended Light	160 to 250	20 to 30	3,000 to 5,000	55 to 65	Instant	85 to 95	Very Low	3500 to 5000
ix)	Metal halide	35 to 2000	80 to 95	4,000 to 12,000	60 to 85	240 to 480	70 to 95	Up to 40 percent	2700 to 4500
x)	High pressure sodium	50 to 1000	90 to 125	10,000 to 32,000	70 to 88	120 to 360	20 to 28	Up to 40 percent	2000 to 3000
xi)	Low Pressure Sodium Sox	10 to 180	65- 100 to 220	8,000 to 15,000	80 to 90	120 to 240	Negative Monochromatic	Not recommended	2400 to 3500
xii)	Induction Lamp	10 to 160	66 to 80	8,000 to 15,0000	60 to 75	Instant	75 to 85	Not recommended	3200 to 5500
xiii)	Single LED white	0.5 to 5	60 to 80	10,000 to1,00,000	60 to 95	Instant	60 to 95	Excellent	2700 to 10000
xiv)	LED System white	2 to 2000	70 to 160	10,000 to 75,000	60 to 95	Instant	60 to 95	Excellent	2700 to 10000
xv)	OLED	0.5 to 60	40 to 80	10,000 to 40,000	85 to 95	Instant	60 to 95	Excellent	2700 to 6500

Table 2 Characteristics /Specification for Incandescent, Low Pressure and High Pressure and Induction Lamps

(*Clause* 4.1)

Sl. No (1)	**Name** (2)	**Optical Spectrum** (3)	**Nominal Efficiency** (lm/W) (4)	**Lifetime (MTTF)** (h) (5)	**Color Temperature** (K) (6)	**Color** (7)	**Color Rendering Index** (8)
i)	Incandescent light bulb	Continuous	4-17	2-20000	2400-3400	Warm white (yellowish)	100
ii)	Halogen lamp	Continuous	16-23	3000-6000	3200	Warm white (yellowish)	100
iii)	Fluorescent lamp	Mercury Line + Phosphor	52-100 (white)	8000-20000	2700-5000*	White (various color temperature) as well as saturated colors available	15-85
iv)	Metal halide lamp	Quasi - continuous	50-115	6000-20000	3000-4500	Cold white	65-93
v)	Sulfur lamp	Continuous	80-110	15000-20000	6000	Pale green	79
vi)	High pressure sodium	Broadband	55-140	10000-40000	1800-2200*	Pinkish orange	0-70
vii)	Low pressure sodium	Narrow line	100-200	18000-20000	1800*	Yellow, no color rendering	0
viii)	Light-emitting diode	Line plus phosphor	10-110 (white)	50,000-100,000	Various white from 2700 to 6000*	Various color temperatures, as well as saturated colors	70-85 (white)
ix)	Induction lamp (external coil)	Mercury line + phosphor	70-90 (white)	80,000-100,000	Various white from 2700 to 6000*	Various color temperatures, as well as saturated colors	70-85 (white)

5 LIGHT EMITTING DIODES (LED)

LEDs are semiconductor diodes that allow current to flow in a single direction. The diode is formed by bringing two slightly different materials together to form a "PN" junction. A PN junction is characterized by an excess of positive charge in the p-type region, represented by holes, and an excess of negative charge in the n-type region, represented by electrons.

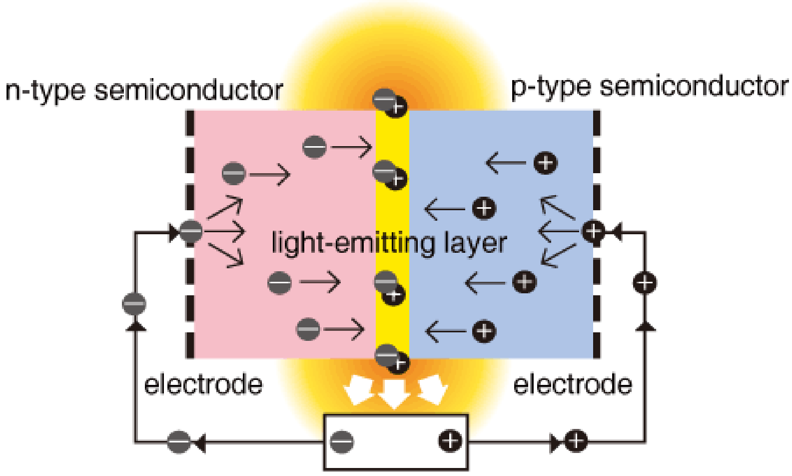


Fig. 2 LED Operation

Upon application of a forward voltage to the semiconducting element forming the 'pn' junction, electrons and holes migrate towards the 'p' and 'n' regions, respectively. Electrons and holes recombine in the vicinity of the junction. During this process, the LED emits light as a result of energy release (*see* Fig. 2). LED devices have a maximum reverse voltage specified by manufacturers, typically rated at 5 V.

Fig. 3 depicts the standard voltage-current correlation for an illumination-grade LED. The figure illustrates that a small alteration in voltage can lead to significant variations in current. LED light output can vary significantly due to the proportional relationship between current and light output.

Exceeding the recommended current limits by the manufacturer can negatively impact the long-term performance of the LED, leading to a shorter useful life. The solid line in Fig. 3 represents the standard operating parameters, while the dotted lines indicate extrapolation.

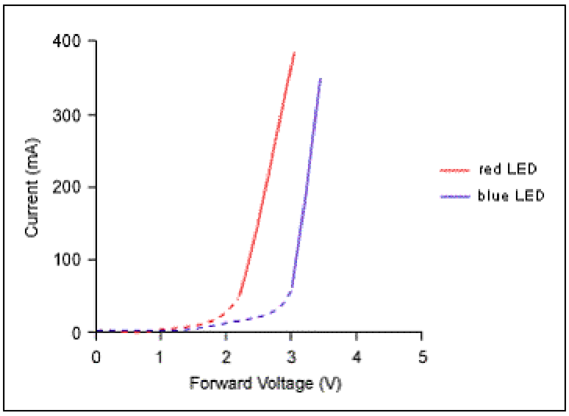


Fig. 3 The Relationship Between Forward Voltage and Current for Illuminator LEDs

6 LED - A LIGHT SOURCE

The discovery of blue LEDs elevated the functionality of LEDs from that of mere indicators to that of illuminators. The PCLED, which is a blue LED chip coated with yellow-emitting phosphor, is capable of producing white light. This process is highly suitable for automation, thereby rendering the LEDs cost-effective for widespread adoption.

Currently, LEDs are the most efficient SSL light sources that can be easily customized to various specifications such as colour, hue, colour fidelity, brightness, spectral distribution, and spatial beam distribution. Additionally, they can be dimmed and colour-tuned. LEDs are durable, small in size, and have a significantly long lifespan.

Various sources of light seen w.r.t their spectral power distribution (*see* Fig. 4).

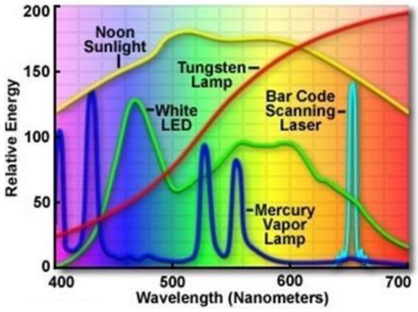


Fig. 4 Various Sources of Light Seen w.r.t Their Spectral Power Distribution

7 LED MATERIAL AND EMISSION COLORS

The electron band gap for the human visible range occurs only in materials made with III-V compounds. Within the visible band, the emission colour is decided by the ratio of compounds GaN-InN, AlP-InP-GaP, and AlAs-GaAs that are built by a slow deposition process cal LED MOCVD (Metal Organic Vapour Phase Deposition) on sapphire and silicon carbide substrates. The latter has eight times more thermal conductivity than the former. The initial layers of a p-n junction LED consist of lattice matching layers, multiple p-doped and n-doped quantum wells, current spreading layers, ohmic matching layers, and transparent electrodes.

Many emerging technologies for the emission of light are being researched (Fig. 5 common LED spectra) like micro LEDs, quantum dots, and nanotube structures.

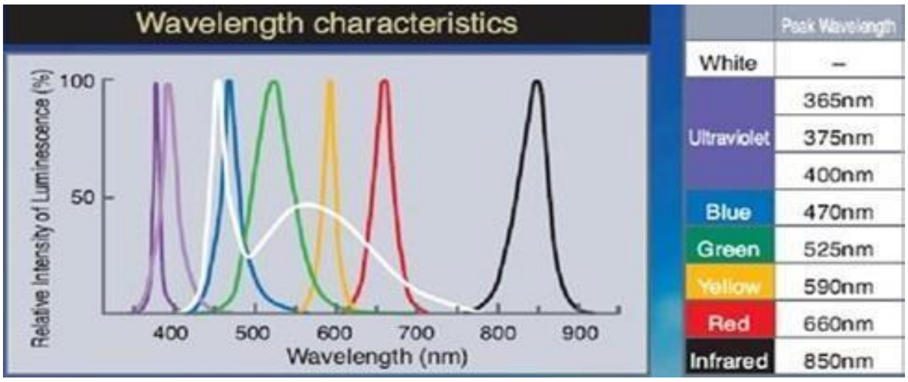


Fig. 5 Common Color Spectra in LEDs

Semiconductor materials used for producing different Colours are listed in Table 3

Table 3 LED Materials and Emission Colors

(*Clause* 7)

Sl No. (1)	Wavelength (2)	Colour (3)	V_f @ 0ma (4)	Material (5)
i)	< 400	Ultraviolet	3.1 - 4.4	AlN, AlGaN, AlGaInP
ii)	400 - 450	Violet	2.8 - 4.0	InGaN
iii)	450 - 500	Blue	2.5 - 3.7	InGaN, SiC
iv)	500 - 570	Green	1.9 - 4.0	AlGaP, AlGaInP, GaP
v)	570 - 590	Yellow	2.1 - 2.2	AlGaInP, GaP
vi)	590 - 610	Orange/ Amber	2.0 - 2.1	GaAsP, AlGaInP, GaP
vii)	610 - 760	Red	1.6 - 2.0	AlGaAs, GaAsP, AlGaInP, GaP
viii)	> 760	Infrared	< 1.9	GaAs, AlGaAs, InP

Aluminium Nitride (AlN)	Aluminium Gallium Nitride (AlGaN)
Aluminium Gallium Indium Nitride (AlGaInN)	Indium Gallium Nitride (InGaN)
Silicon Carbide (SiC)	Aluminium Gallium Indium Phosphide (AlGaInP)
Gallium Phosphide (GaP)	Gallium Arsenide Phosphide (GaAsP)
Aluminium Gallium Arsenide (AlGaAs)	Gallium arsenide (GaAs)

7.1 Manufacturing Process of White LEDs

The LED chip is selected based on the required power capacity and then attached to the desired package size using the die attach process. The Wirebond process involves using 25-micron Gold, Alloy, or Copper wires to thermosonically bond electrode pads of a chip to package terminals. The phosphor is uniformly dispersed in silicone using a vacuum centrifugal mixer, and then accurately deposited onto the LED chip located in the reflector lead frame. The mixture is subsequently thermally cured. The LEDs undergo a 100 percent testing process and are automatically sorted into specific groups based on their colour (CCT, XY values), lumens (L_m), and forward voltage (V_f) combinations.

Below Fig. 6 shows LED internal structure and Fig. 7 shows complex structure of multiple quantum wells and epilayers of lattice matching, current spreading and light extraction inside a LED die.

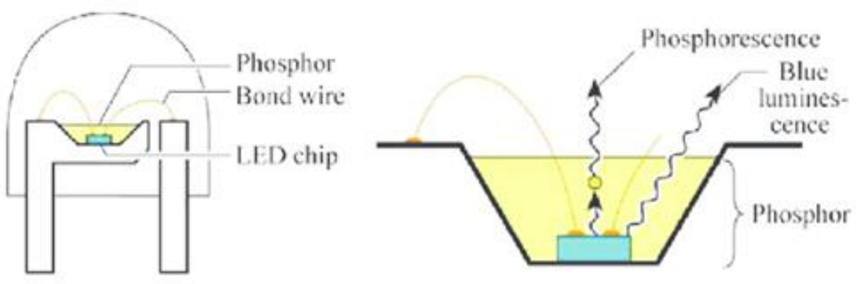
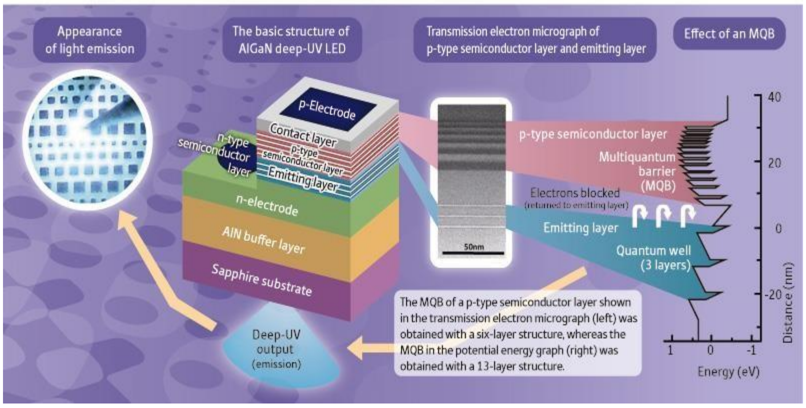


Fig. 6 LED Internal Structure



The MQB of a p-type semiconductor layer shown in the transmission electron micrograph (left) was obtained with a six-layer structure, whereas the MQB in the potential energy graph (right) was obtained with a 13-layer structure.

Fig. 7 Complex Structure of Multiple Quantum Wells and Epilayers of Lattice Matching, Current Spreading and Light Extraction Inside a LED Die

There are three main methods of mixing colours to produce white light from an LED (*see* Fig. 8).

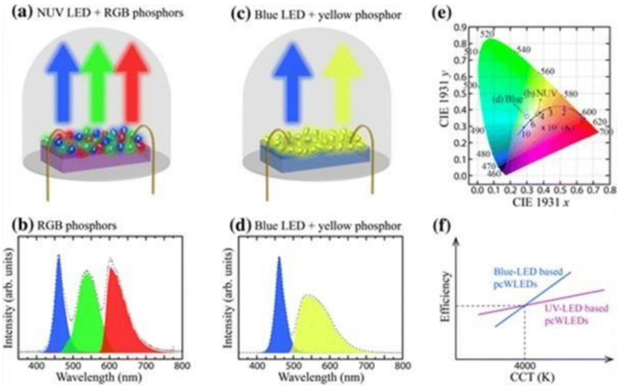


Fig. 8 Colour Mixing of LEDs

a) Red LED + Green LED + Blue LED (colour mixing as in active displays);
b) Near-UV or UV LED + RGB phosphor (as in Fluorescent Tubes); and
c) Blue LED + yellow phosphor – (mixing two complementary colours).

The blue chip is selected as a source due to its high efficiency in blue emission. Applying a phosphorus coating to the chip can transform a portion of the blue energy into yellow. By regulating the phosphor quantity, we can achieve net emission in the form of cool white (6000K CCT), neutral white (4500K), or warm white (3000K). Increasing the amount of red and green phosphor enhances the LED light's colour rendering index (CRI) and produces a more comprehensive range of colours.

The phosphor types are YAG, TAG, silicates, nitrates, etc. doped with rare earths like Ce, Eu, Tb/Dy etc., giving us a wide choice of emission peaks to achieve any desired colour.

8 ANATOMY OF MODERN LEDS and COMMON LED TYPES AND PACKAGES

Below Fig. 9 shows internal construction of the LED (lead frame, chips and encapsulant).

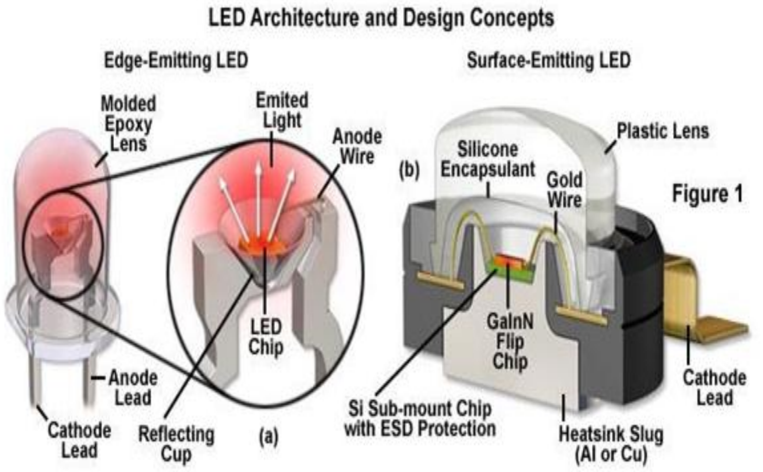


Fig. 9 Inside the LED - Lead frame, Chips and Encapsulant

8.1 Direct View Application

It refers to a lighting design application that involves lamps and/or luminaires that are specifically intended to be viewed directly, rather than being used for general illumination purposes. Illustrative instances comprise sparkle effects, navigational markers, and media walls.

8.2 LED Packaging

A LED package is comprised of one or more LED dies, wire bond connections, and may include an optical element, as well as thermal, mechanical, and electrical interfaces. The device lacks a power source, a base, and direct connection to the branch circuit.

8.3 LED Luminaires

This is a comprehensive LED lighting system that includes a light source, driver, light distribution components, protective housing for the light source, and connection to a branch circuit. Below Fig. 10 shows LED package types.

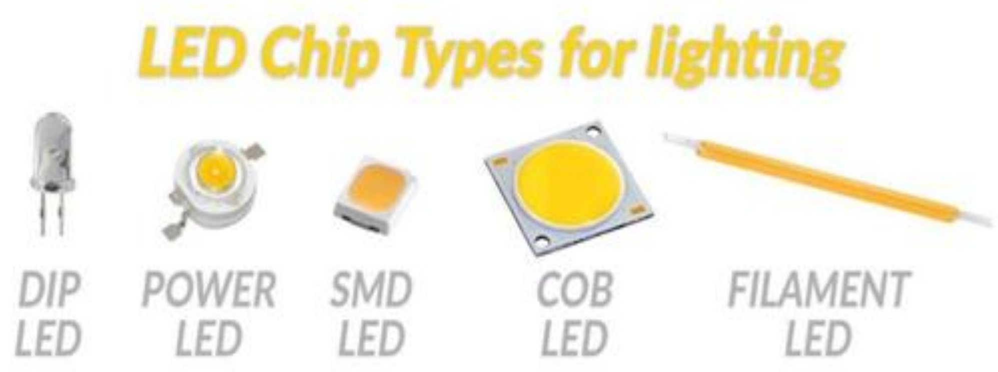


Fig. 10 LED Package Types - DIP, Power, SMD COB, Filament LEDs

8.4 DIP LED

DIP (Dual In Package) LEDs, also known as through-hole LEDs, feature axial leads made of silver or tin-plated iron and a chip enclosed in durable epoxy. The beam angle of an epoxy lens can vary from 8° to 140°, depending on the lens shape and chip positioning. Typically, these devices possess a 20 mA rating and are available in bipolar (2 leads), bicolor (3 leads), and tricolour (4 leads) leadframe configurations. The LED chip can be configured for plug-and-play either with an IC for RGB flashers or with an embedded resistor. DIP LEDs are commonly used as indicators of status and in mobile signage.

8.5 SMD Chip

SMD, Surface Mount Device LED, have small footprint and also a thermal path through a inner heat slug, copper or metal alloy base, injection molded body of PPA (0.2W, 0.5W), or PCT (1W) or EMC (1W above). SMD can be Multiple Chips and Multiple terminals type. SMD are made for fast automated electronic assembly.

8.6 Chip on Board (COB)

COB refers to a technology in which multiple electronic components are mounted on a single substrate, resulting in a compact and efficient design. The defined light emitting surface houses several diode chips. The design of optics considers COB as a singular point source. It mitigates the nuisance of multiple shadows that are linked to LED arrays. COBs achieve high light spatial density. However, improved thermal management is required for the concentrated heat produced. COB technology eliminates the requirement for printed circuit boards (PCBs), reduces the necessity for costly surface-mount technology (SMT) soldering lines, and streamlines the production of LED lighting. Reflector optics are typically preferred for spot lights, while lens optics are commonly used for outdoor lights.

8.7 Flip Chip (FC) LEDs and CSP LED

In Flip Chip version, the electrode pads and thermal pads are expanded and at same plane, allowing direct solder to the PCB. FC LEDs can be coated with Phosphor individually through a process.

8.8 Filament LED

The need for retrofit for chandeliers and squirrel cage bulbs, gave birth to filament LEDs on narrow strips weldable like classic tungsten filaments.

9 LED ARRAY, LED MODULE AND LED LAMPS and LUMINAIRE

An LED Array is a collection of LED packages on a printed circuit board or substrate, which may include optical elements and additional thermal, mechanical, and electrical interfaces. An LED module comprises of one or multiple LEDs that are connected to the load side of an LED driver, along with optional electrical, electronic, optical, and mechanical components.

An LED lamp AND Luminaire is a self-contained lighting unit that includes a light source, driver, components for light distribution and protection, and connection to a branch circuit.

Effective utilization of LEDs necessitates efficient thermal coupling among the LED package, luminaire, and design application.

10 USING LED DATASHEETS FOR SELECTION OF FLUX, CCT COLOUR, CRI

A universal nomenclature for defining all characteristics of an LED does not exist. A multipage datasheet effectively conveys the pertinent characteristics. The provided data pertains to physical dimensions, as well as the highest values for d.c. current, peak forward current, LED junction temperature, reverse voltage limit, and operating and storage temperature ranges. The electrical and optical specifications for forward voltages (V_f), luminous flux/intensity, dominant wavelength or Correlated Colour Temperature (CCT) x,y range, and view angle are provided for a given test current, including minimum, typical, and maximum values. The data sheet may include graphs depicting the relationship between wavelength shift and forward current, relative output and forward current, spectral power distributions, and a polar plot of luminous intensity. Operational data is temperature-sensitive and usually referenced to a 25 °C ambient temperature in data guides.

The challenge is to choose an appropriate LED and driver combination that can produce the desired level of illumination. The LED temperature often rises rapidly in various applications, resulting in decrease in lumen output. Datasheets for high power LEDs provide information on hot lumens at 85 °C.

If one needs to know the light output of a brightest available LED at a design current of say 2100mA, we start with selection a LED from the brightest bin V5. The 460 lumens (see the highlighted number) is the typical flux at 1050mA (the manufacturer’s test current).

Following the curve to 2100mA we see that this is a 75 percent increase in light. Taking the 460 lumens from ratings table and multiplying it by 1.75 we can see that the same LED running at 2100mA gives off about 805 Lumens.

11 OPTICAL OUTPUT IN FLUX OR INTENSITY

Luminous Flux Φv is the total optical power coming out of a Light Source. Its measured in lumens with the help of a calibrated Integrating Sphere or Goniophotometer.

Luminous Intensity I_v is the luminous flux emitted per solid angle. A candela is defined as one lumen per steradian. It is measured in candela with the help of a calibrated Goniophotometer.

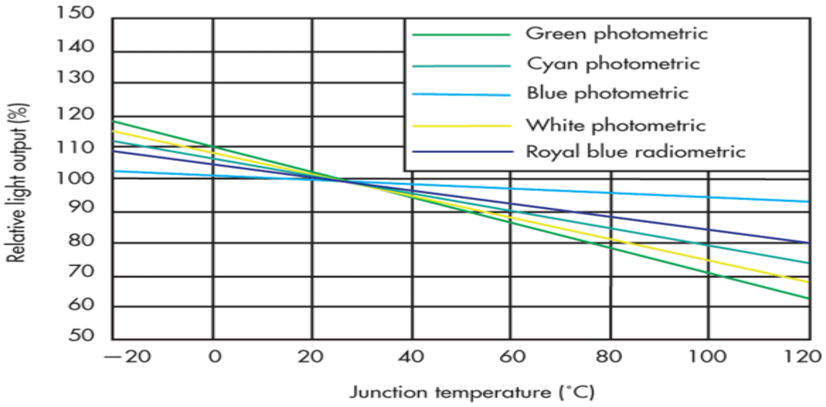


Fig. 11 Temperature vs Light Output. As Temperature Increases the Output Reduces.

As the lumen output at 85°C could go down significantly, the luminaires are designed with the data at 85°C, that is with ‘hot lumens’, to be in line with reality. At 25°C is the optimum design value. *See* Fig. 11.

12 CCT OR X, Y COORDINATES OR WLD

The correlated color temperature (CCT) of a given color is the temperature at which a black body emits the same color. Fig. 12, shows the CCT as seen different session w.r.t sun or candle light.

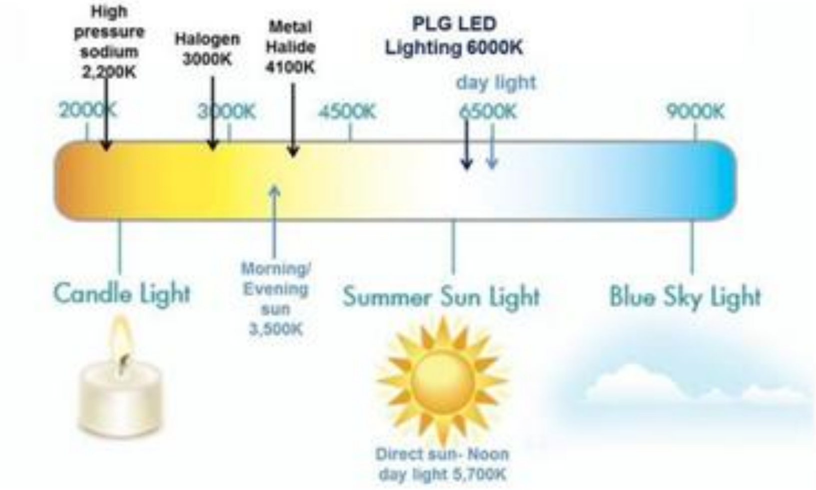


Fig. 12 CCT of Natural and Legacy Light Sources

For the white and mixed colors the LEDs are measured for x and y coordinates of CIE1937 curve. Corresponding CCT line on which this x, y point lies, is a more convenient parameter to comprehend the color and hence preferred parameter of color measurement.

13 LED EFFICACY

The LEDs have come a long way in efficiency up from 30 lm/W to 140-180 lm/W. A laboratory green LED at 555 nm has produced 683 lumens per watt, the absolute maximum for human eye as shown in Fig. 13. Since white light is obtained by adding blue and red, to which eye response is poor, we end up with theoretical maximum of about 250 lm/W in White LEDs. Details of CCT vs lumen per watt (efficacy) plot for various light sources and LED light sources. Below Fig. 14 shows plot for lm/W versus colour temperature.

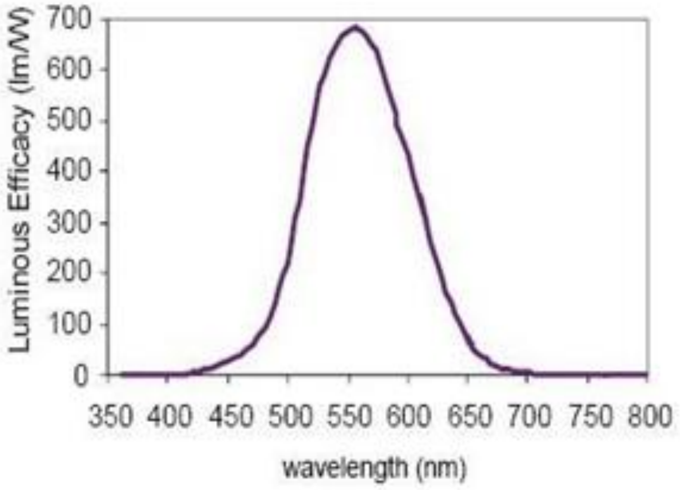


Fig. 13 Luminous Efficacy Versus Wavelength

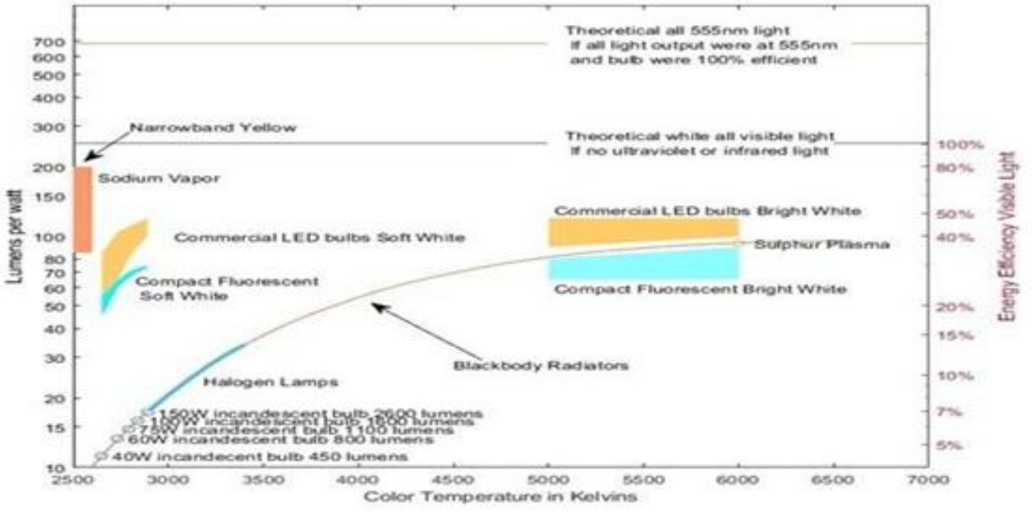


Fig. 14 Plot for lm/W versus Colour Temperature

14 COLOR UNIFORMITY AND BINNING

Uniformity issues arise from the inherent complexities of semiconductor manufacturing, as different areas of the wafer and variations between batches inevitably result in differing properties. Human eye, though having less sensitive logarithmic response to brightness, detects smallest difference in color space, measured in McAdam Steps, which result from unavoidable variance in phosphor volume or density.

To address this, a process called binning is employed, where automated machines test LEDs and sort them into categories, or bins, based on similarities in lumens, color, and voltage. Among these, lumens and color are the most critical parameters in LED variability. This process ensures that batches of LEDs have only minimal deviations in performance. Fig. 15 explains details of area of the colour deviation I colour temperature vs x-y coordinates or colour space.

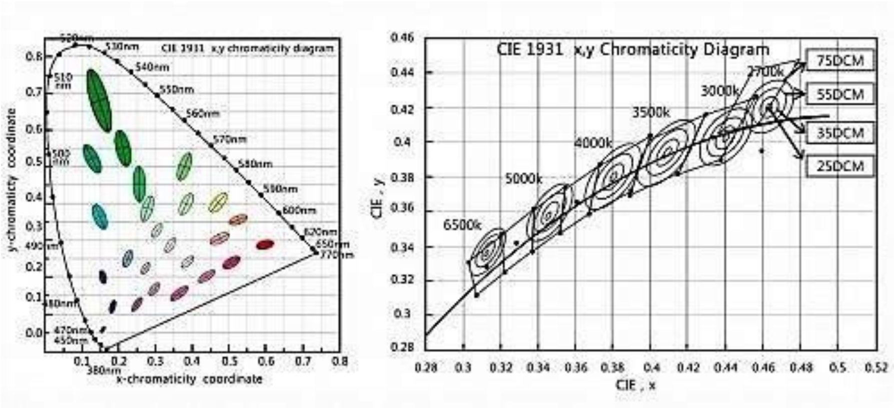


Fig. 15 The Plot Depicting Width of SDCM or Mcadam Step Varies by Location in Color Space

15 STANDARD DEVIATION COLOUR MATCHING (SDCM)

SDCM as shown in Fig. 16 has the same meaning as a “MacAdam ellipse”. A 1-step MacAdam ellipse defines a zone in the CIE 1931 2 deg (xy) colour space within which the human eye cannot discern colour difference. The size of an SDCM ellipse is quite small, which means that the human vision system is very good at discriminating colour differences when viewing two light sources at the same time. Most LEDs are binned at the 4-7 step level, in other words you certainly can see colour differences in LEDs that are ostensibly the same colour.

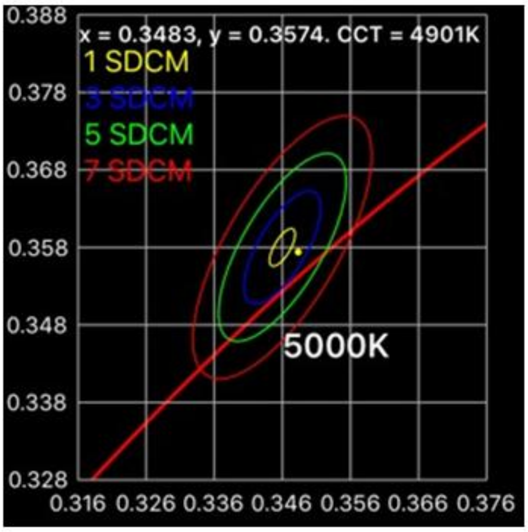


Fig. 16 Plot Showing the SDCM for LEDs

16 COLOR STABILITY

Some LEDs shift in color with changes in the junction temperature, which may be a result of dimming. It is not possible to generalize the magnitude of the color shift. AlInGaP LEDs (above about 580 nm) tend to have larger colour shifts with a change in temperature than to InGaN LEDs (below about 550 nm). LED lamps may also shift in color as they age, and different spectral components may have unequal lumen depreciation. Some multimodal LED systems that create white light with the additive mixing of red-, green-, and blue-emitting LEDs employ active feedback to hold chromaticity constant during dimming and over life. This is achieved by differentially adjusting the red, green, and blue emitting components. LED lamps that employ a phosphor tend to be less susceptible to color shift with respect to both diming and life. Below Fig. 17 shows graphical representation of the chromaticity specification of nominally white SSL production. Table 4 shows Chromaticity of Various White CCTs**.**

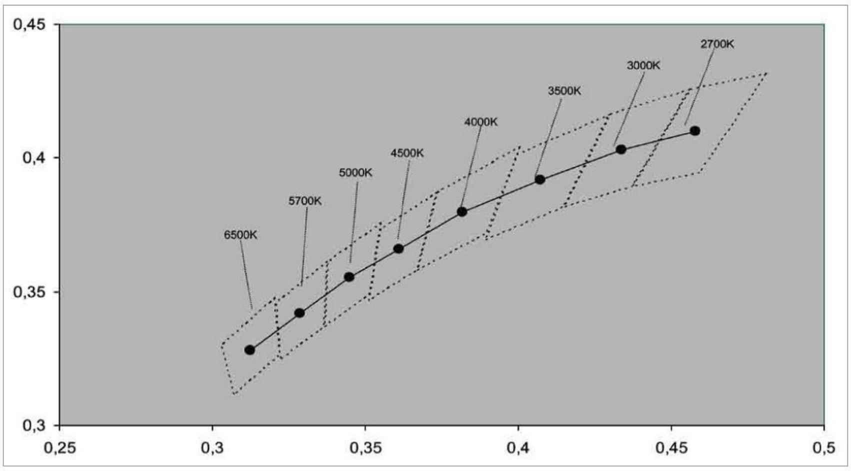


Fig. 17 Graphical Representation of the Chromaticity Specification of Nominally White SSL Production

Table 4 Chromaticity of Various White CCTs wrt to ANSI C378.377 Has Been Clearly Sated the Tolerance

(*Clause* 16)

Sl No.		**2700 K**		**3000 K**		**3500 K**		**4000 K**		**4500 K**		**5000 K**		**5700 K**		**6500 K**	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
i)	**Center point**	0.4578	0.4101	0.4338	0.4030	0.4073	0.3917	0.3818	0.3797	0.3611	0.3658	0.3447	0.3553	0.3287	0.3417	0.3123	0.3282
ii)	**Tolerance Quadrangle**	0.4313	0.4319	0.4562	0.4260	0.4299	0.4165	0.4006	0.4044	0.3736	0.3874	0.3551	0.3760	0.3376	0.3616	0.3205	0.3481
		0.4562	0.4260	0.4299	0.4165	0.3996	0.4016	0.3736	0.3874	0.3548	0.3736	0.3376	0.3616	0.3207	0.3462	0.3028	0.3304
		0.4373	0.3893	0.4147	0.3514	0.3889	0.3690	0.3670	0.3578	0.3512	0.3465	0.3366	0.3369	0.3222	0.3243	0.3063	0.3113
		0.4593	0.3944	0.4373	0.3893	0.4147	0.3814	0.3898	0.3716	0.3670	0.3578	0.3515	0.3487	0.3366	0.3369	0.3221	0.3261

17 Duv

A Duv value provides information on the distance and direction of a color shift from the Planckian locus on the CIE 1960 u-v coordinates. When Duv value is closer to zero, the light source is more like an ideal one.

Table 5 shows the Nominal CCT and Duv values defined by C78.377

Table 5 CCT Tolerance Value as Per CIE
(*Clause* 17)

Sl. No	**Nominal CCT**	**Target CCT and Tolerance (K)**	**Target D_{uv} and Tolerance**
(1)	(2)	(3)	(4)
i)	2700K	2725 ± 145	0.000 ± 0.006
ii)	3000 K	3045 ± 175	0.000 ± 0.006
iii)	3500 K	3465 ± 245	0.000 ± 0.006
iv)	4000 K	3985 ± 275	0.001 ± 0.006
v)	4500 K	4503 ± 243	0.001 ± 0.006
vi)	5000 K	5028 ± 233	0.002 ± 0.006
vii)	5700 K	5665 ± 355	0.002 ± 0.006
viii)	6500 K	6530 ± 510	0.003 ± 0.006
ix)	Flexible CCT (2700-6500 K)	T ±ΔT	D_{uv} ± 0.006

18 CRI of LED

Colour Rendering Index (CRI) is a measure of how similar object colors appear under illumination by a test source compared to the object colours under midday sun.

Ra = average of R1 to R8 and Re = average of R1 to R15. R9 the saturated red is difficult to achieve and needs right phosphor mix. Below Fig. 18 shows CRI histogram with R1 to R15 values and Fig. 19 shows LED spectra.

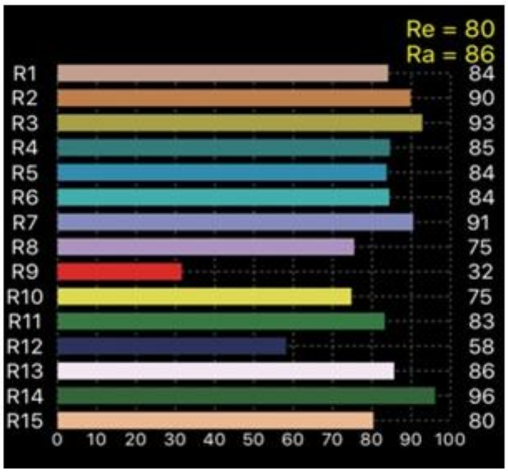
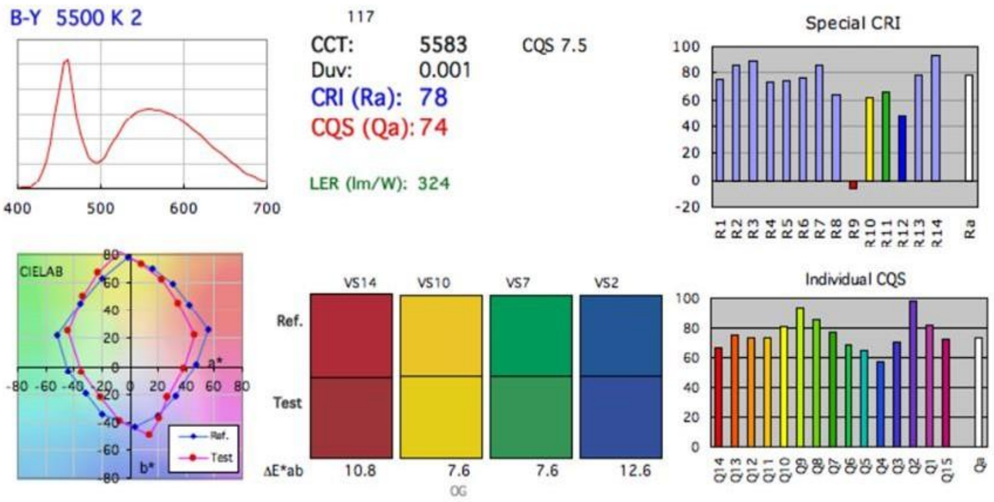


Fig. 18 CRI Histogram with R1 to R15 Values



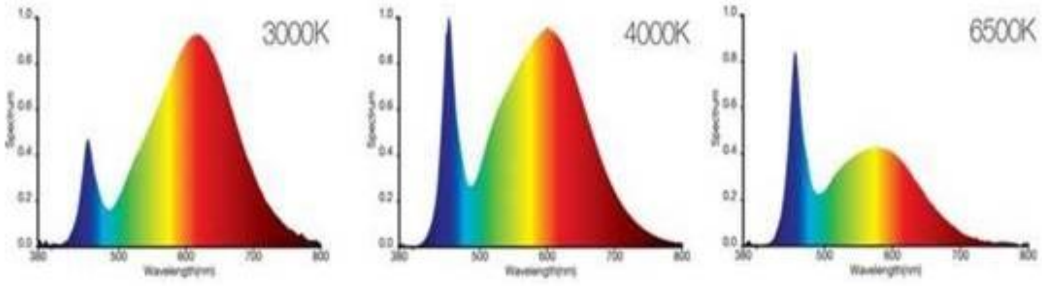


Fig. 19 LED Spectra for 3000K 95Ra vs 4000K 94Ra vs 6500K 70Ra

19 COLOR FIDELITY

Light detectors in the EYE are rods and cones. The cones are three types, each responds a portion of the spectrum, with peaks of blue, green, and red light. The interaction of these groups is then responsible for the stimulus which is interpreted by the brain as color. This theory on color vision is Trichromatic Theory.

LED light sources achieve a wide range of color qualities, depending on the requirements of the lighting application. High levels of color quality generally measured by CRI, there are typically cost and efficiency trade-offs most of the times. Below Fig. 20 shows calculation of CRI Ra for colours.

Fig. 20 Colours used to calculate CRI Ra

A CRI of 80 recommended for interior lighting. CRI of 90 or higher indicates excellent color fidelity; LEDs can also meet this threshold.

CRI is far from a perfect metric and is especially poor at predicting the fidelity of saturated reds, for which the supplemental value R_9 is often used. Color rendition perceptions can vary with chromaticity, with an interactive effect of CCT and Duv. New metrics, such as the fidelity index (R_f) and the gamut index (R_g), which are described in IES TM-30-15, can provide a more comprehensive evaluation of color rendering.

Instead of a single fidelity value, as with CRI Ra, TM-30-15 IES Method for Evaluating Light Source Color Rendition gives us a wealth of data about the color rendering of the light source in question. The first is the Fidelity Index R_f. Like Ra, it is a comparison of the color rendering of the test light source compared to the reference light source. However, with 99 color samples it isa tougher test that cannot be gamed.

The second is the Gamut Index R_g. R_g indicates the average change in saturation of the 99 color samples as rendered by the test source compared to the reference source.

A gamut index of 100 means that, on average, the test light source doesn't change the hue or saturation of the CES compared to the reference source. An R_g above 100 indicates that the test light source, on average, increases the saturation of the CES producing colors that are more vivid.An R_g below 100 indicates that the test light source decreases the saturation of the CES producingcolors that are less saturated. Below Fig. 21 shows relation between R_g and R_f.

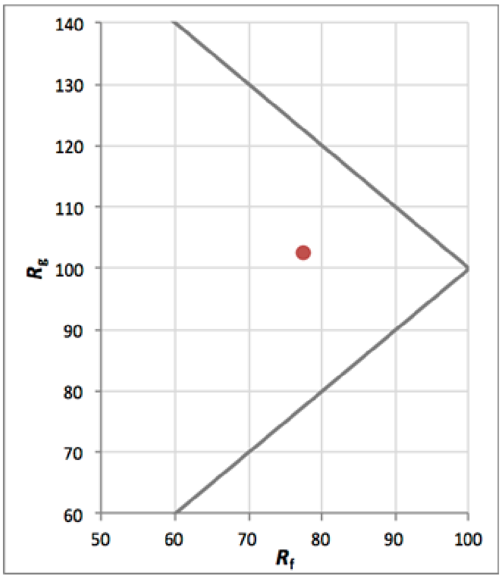


Fig. 21 Relation of R_g vs R_f

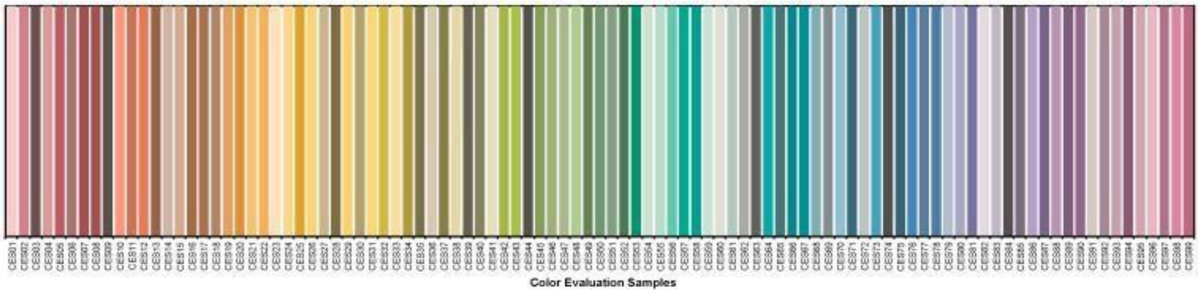


Fig. 22 Colours Used in the TM-30 Chosen Across CAM02 UCS The Most Modern ColourSpace.

The color distortion icon, is plotted on the CAM02-UCS color space. In this graphic Fig. 22 boththe reference source and the test source are shown, along with an indication of the direction and magnitude of the hue shift caused by the test source. Finally, we can even look at the color shift for each of the 99 CES.

A designer using TM-30 now has three big picture metrics to evaluate a light source: color fidelity(R_f), color gamut (R_g), and correlated color temperature (CCT). The designer can use TM-30's calculation tool to examine the R_f and R_g of a light source in as much detail as the project merits, from a very broad overview to a very detailed, color by color, evaluation. Below Fig. 23 shows TM-30 16 sectors and colour circle.

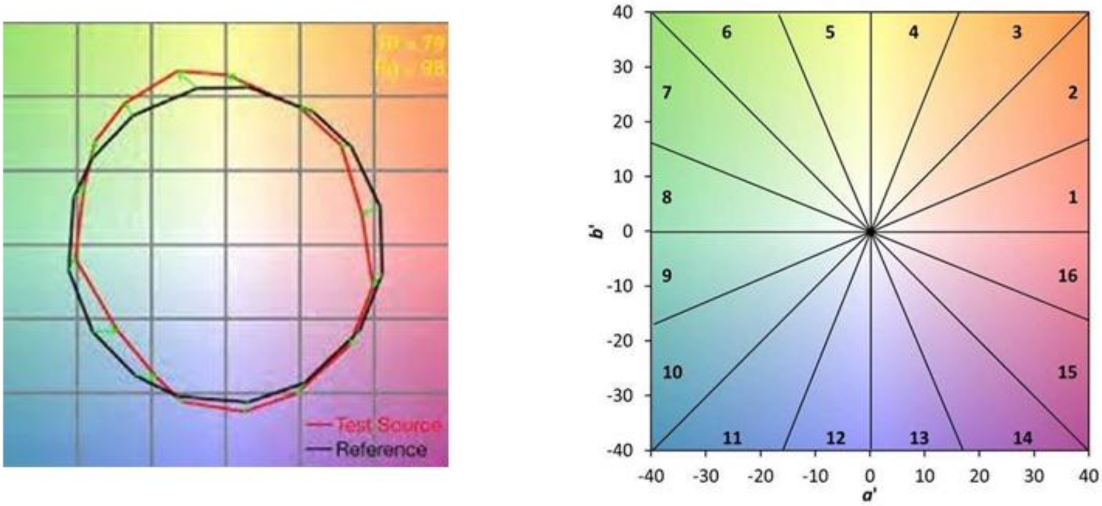
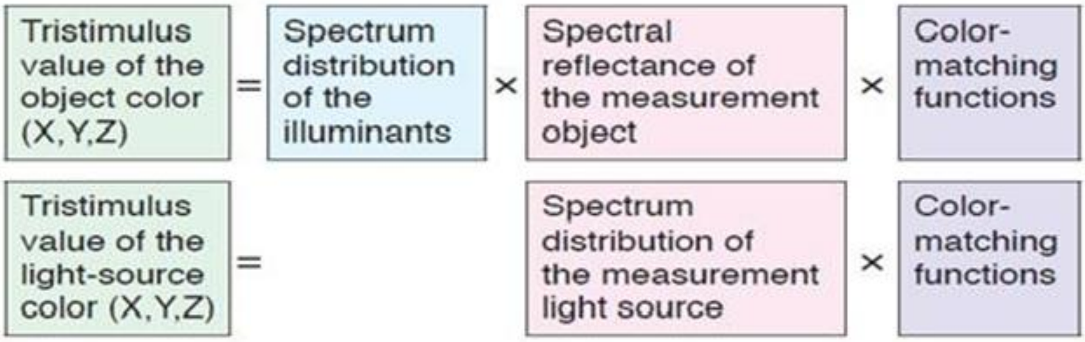


Fig. 23 TM-30 16 Sectors and Colour circle

20 COLORIMETRIC CALCULATIONS

The chromaticity (x,y) CIE 1931 and / or (u',v',) CIE 1976 and correlated color temperature (CCT,unit: Kelvin) are calculated from the relative spectral distribution of the SSL product. Below Fig. 24 shows calculation of x,y,z in CIE 1931 and Fig. 25 shows space chromaticity diagram.



Tristimulus value of the object color (X,Y,Z) = Spectrum distribution of the illuminants × Spectral reflectance of the measurement object × Color-matching functions

Tristimulus value of the light-source color (X,Y,Z) = Spectrum distribution of the measurement light source × Color-matching functions

Fig. 24 Calculation of x,y,z in CIE 1931

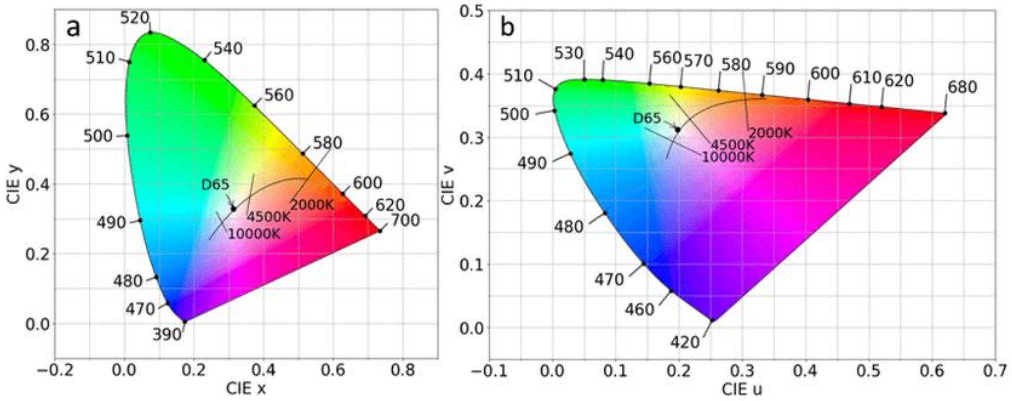


Fig. 25 The CIE 1931 (X,Y) and CIE 1976 UCS Color(U′, V′) Space Chromaticity Diagram. The Outer Curved Boundary is the Spectral (or Monochromatic) Locus.

21 CHROMATICITY AND DOMINANT WAVELENGTH FOR LE

Below Fig. 26 shows dominant wavelength WLD is the peak as perceived by the skewed eye sensitivity and Fig. 27 shows dominant wavelength of various compounds.

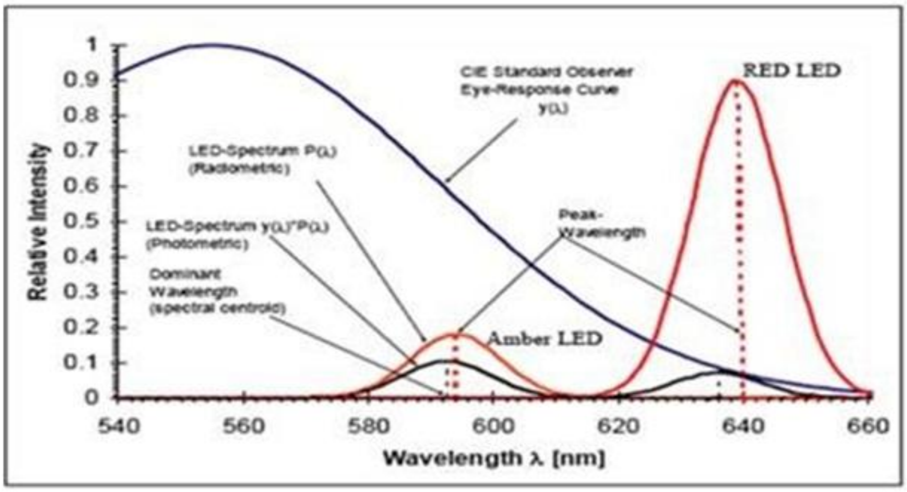


Fig. 26 Dominant Wavelength WLD is the Peak as Perceived by the Skewed Eye Sensitivity

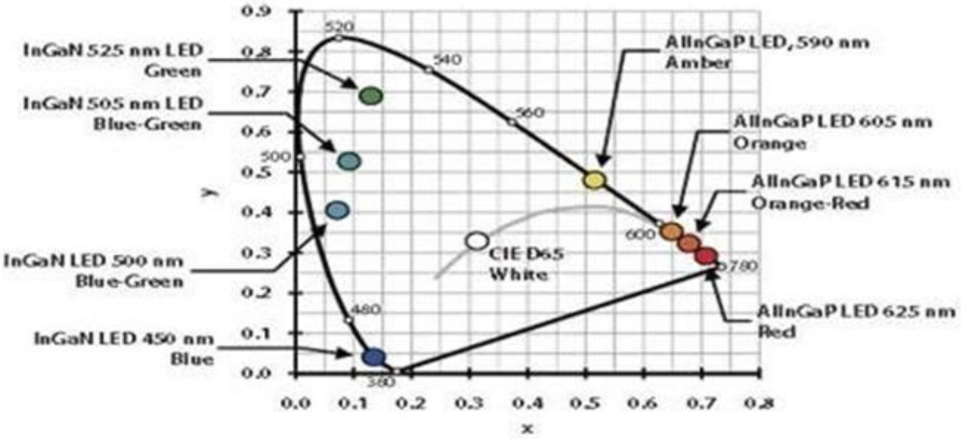


Fig. 27 Dominant Wavelength of Various Compounds

22 SPECTRAL POWER DISTRIBUTION

In radiometry, photometry, and colour science, a spectral power distribution (SPD) measurementprovides information about the power per unit area per unit wavelength of an illumination sourceor radiant exitance. It describes the distribution of radiant energy across the electromagnetic spectrum.

SPDs (*see* Fig. 28) are commonly used to characterize the colour properties of light sources. They can be measured and represented graphically, showing the intensity or power at each wavelength. By examining the shape and distribution of the SPD, we can understand the spectral composition of light emitted by a particular source.

Chromaticity is another important concept related to SPDs. It refers to the quality of colour of a light source and is determined by its relative proportions of different wavelengths. Chromaticity coordinates, such as x and y or u' and v', are often used to represent the color properties of a lightsource on a chromaticity diagram, such as the CIE 1931 xy or CIE 1976 uv chromaticity diagram.

The dominant wavelength of a light source represents the wavelength at which its spectral powerdistribution peaks or has the highest intensity. It is a measure of the perceived color of the light source. For monochromatic light sources, such as lasers, the dominant wavelength corresponds tothe single wavelength emitted.

When comparing different light sources, their SPDs can be evaluated based on how close they plotto the spectrum locus on a chromaticity diagram. The spectrum locus represents the range of colours visible to the human eye and corresponds to monochromatic light at various wavelengths.Light sources that plot closer to the spectrum locus generally have a narrower spectral power distribution and may exhibit more saturated or pure colours.

SPDs are often displayed with normalized values for convenience, where the values are scaled to a maximum of 1. This normalization allows for easier comparison and analysis of different SPDs.

Overall, spectral power distribution measurements provide valuable insights into the color properties and composition of light emitted by various sources, enabling a deeper understanding of light and its interaction with objects and the human visual system.

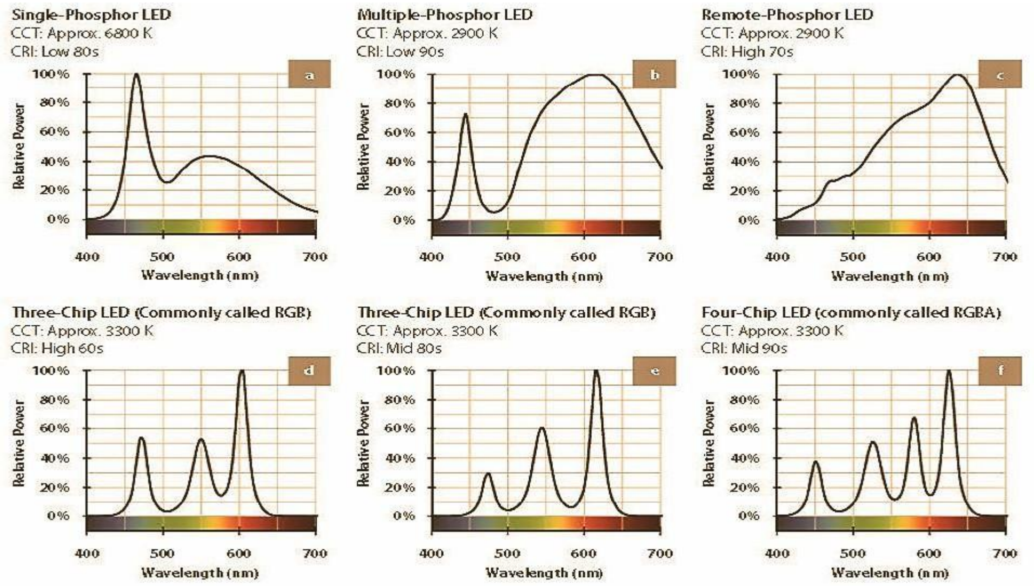


Fig. 28 SPD of LEDs

23 COLOR TUNING OF A LED LIGHT SOURCE

The use of RGB LEDs per pixel enables color-changing effects in displays by varying the current through red, green, and blue LEDs. In lighting, adjustable cool and warm white LEDs are used for mood and circadian lighting by tuning their current ratio, supporting wakefulness or sleep. In horticulture, LED systems with blue, yellow, and red LEDs optimize plant growth by providing tailored light spectra for different stages. LED technology offers precise, dynamic color control for applications like displays, mood lighting, circadian lighting, and horticulture.

24 LED LIFE AND THERMAL CHARACTERISTICS

Heat significantly impacts LED characteristics such as lumen output, efficacy, color, and lifespan, as it directly affects the p-n junction temperature. Efficient thermal management, including optimized LED package designs, heat sinks, thermal interfaces, and ventilation, helps dissipate heat and maintain lower junction temperatures, preserving LED performance and longevity.

While LEDs efficiently convert electricity into light, a notable portion of energy is still dissipated as heat, leading to high heat density compared to traditional lighting. Excessive heat can degrade performance, color stability, and lifespan, making heat management crucial, especially in high-power applications like lighting, automotive, and displays.

Advancements in LED technology focus on improving crystal structures, enhancing light extraction, reducing internal photon reabsorption, and minimizing efficiency loss from effects like Auger recombination. These efforts aim to optimize performance, reliability, and lifespan while mitigating thermal challenges.

25 EFFICIENCY AND LIGHT OUTPUT

Higher temperatures can decrease the efficiency of LEDs, leading to reduced light output. The conversion of electrical energy to light becomes less efficient as the temperature rises, resulting inlower overall luminous efficacy. This can affect the brightness and quality of the emitted light, impacting the LED's intended application.

25.1 Color Shift

LEDs are available in various colors and color temperatures. However, excessiveheat can cause a color shift, altering the perceived color of the emitted light. This can be particularly problematic in applications where color accuracy is crucial, such as display screens, signage, or architectural lighting.

25.2 Degradation and Lifespan

Heat is a major contributor to LED degradation and can significantly impact its lifespan. Elevated temperatures accelerate the aging process of the LED, leading to a shorter operational life. The excessive heat can degrade the LED's semiconductor materials, reducing its reliability over time.

25.3 Thermal Stress

Rapid and extreme temperature changes, such as thermal cycling, can induce thermal stress in the LED. The difference in expansion and contraction rates between the LED materials and the surrounding components or solder can lead to mechanical stress and potentially result in cracking or delamination, compromising the LED's integrity.

To mitigate the impact of solder point temperature on LEDs, proper thermal management is crucial. This includes:

25.3.1 *Heat Dissipation*

Efficient heat dissipation is essential to maintain the solder point temperature within acceptable limits. Heat sinks, thermal pads, or thermal interface materials helpconduct heat away from the LED and into the surrounding environment or a dedicated heat sink.

25.3.2 *Adequate Design*

Proper LED packaging and circuit board layout can facilitate heat transfer and minimize temperature rise. Designs that incorporate thermal vias, copper traces, or thermal pads can enhance heat dissipation and distribute the heat more evenly.

25.3.3 *Thermal Monitoring*

Temperature sensors or thermal monitoring systems help maintain safe solder point temperatures by providing real-time feedback and enabling corrective measures. Properly managing this temperature optimizes LED performance, reliability, and lifespan, ensuring consistent light output and color stability.

Unlike filament bulbs, LEDs absorb excess heat, increasing junction temperature and reducing photon efficiency. Effective heat dissipation, often via metal housings, can extend LED lifespan by up to ten times. Heat flows from the LED chip to the metal core PCB and aluminum lamp body, which features finned designs to enhance convective cooling. Adequate air ventilation around the luminaire is essential for optimal heat management.

Below Fig. 29 shows importance of Thermal Interface Materials (TIM) in LED bulbs and luminaires.

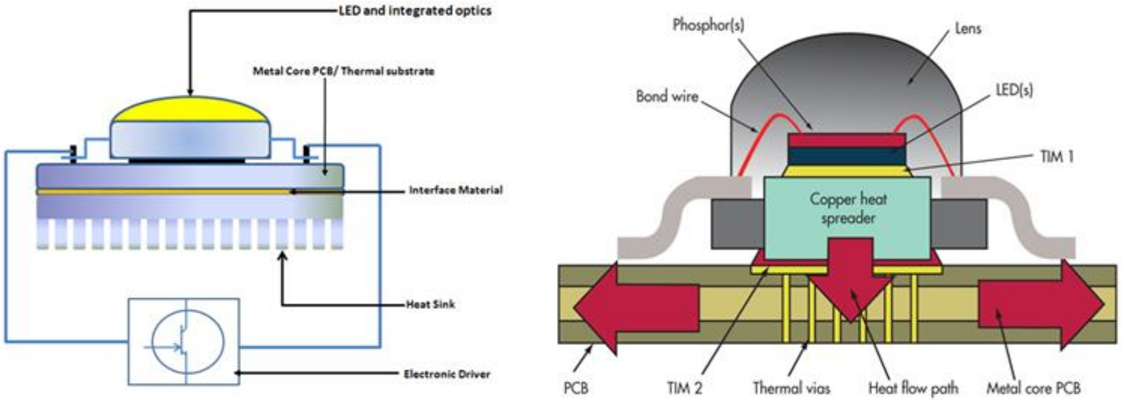


Fig. 29 Thermal Interface Materials (TIM)

26 TIM- THERMAL INTERFACE MATERIAL

The importance of thermal management and the role of a Thermal Interface Material (TIM) in ensuring effective heat transfer in LED applications.

The interface between the LED and the MCPCB (Metal Core Printed Circuit Board) or the MCPCB and the metal housing often contains tiny air voids, which act as thermal barriers and impede heat flow. To address this issue, it is crucial to use a thermally conductive paste or TIM tofill these voids and establish good thermal contact between the surfaces. Applying the TIM and using appropriate fasteners to tightly press the surfaces together helps eliminate air gaps and improves heat transfer.

Additionally, achieving a high level of surface planarity between the MCPCB and the housing is important to optimize heat dissipation. This ensures efficient thermal conduction from the LED tothe heatsink and facilitates the transfer of heat to the surrounding environment.

When it comes to selecting a heatsink, the mass of the heatsink itself is less critical than maximizing the fin surface area for enhanced convection losses. Increasing the surface area allows for better heat dissipation into the ambient air. It is also essential to use a high conductivity TIM to facilitate the transfer of heat from the LED to the heatsink, enabling the LED to operate at lowertemperatures.

It's worth noting that if plastic enclosures are placed over the heatsink body for aesthetic purposes,they can hinder heat evacuation and reduce the effectiveness of the heatsink. Proper considerationshould be given to the design to ensure that heat can efficiently dissipate from the heatsink.

The importance of thermal management lies in maintaining a lower LED junction temperature. Even a small reduction in temperature, such as 10 °C, can significantly extend the LED's workinglife by as much as 20,000 hours. Therefore, it is crucial to prioritize thermal design and strive to reduce every degree of heat to maximize the LED's lifespan.

The improvement in LED packages and their thermal design has played a significant role in reducing the thermal resistance (R_{th}) and enhancing overall thermal management.

LED packages have undergone advancements to improve their ability to dissipate heat efficiently.These improvements include optimizing the design of the package to minimize thermal resistanceand enhance thermal conductivity. The development of new materials, such as high thermal conductivity substrates and encapsulants, has also contributed to better heat dissipation.

By reducing the thermal resistance from the LED chip to the terminal pads, the heat generated within the LED can be more effectively transferred to the surrounding environment. This helps inmaintaining lower junction temperatures and improves the overall thermal performance of the LED.

The evolution of LED packages has seen the introduction of various designs, such as ceramic packages, metal-core packages, and flip-chip packages, each offering different thermal propertiesand performance characteristics. These advancements have allowed for better heat transfer,improved thermal stability, and increased reliability of LED products.

Optimizing thermal management not only enhances the LED's performance and efficiency but alsoextends its overall lifespan. By effectively dissipating heat and maintaining lower junction temperatures, the LED can operate under more favorable conditions, reducing the risk of thermalstress and degradation.

Therefore, it is essential to consider the thermal characteristics and design of LED packages whenselecting LEDs for specific applications. The continuous improvement in LED package designs and thermal management techniques provides opportunities for achieving better performance, reliability, and longevity in LED lighting systems. Fig. 30 given typical example of thermal resistance of LED packages and thermal profile for different LED packages shown in Fig. 31.

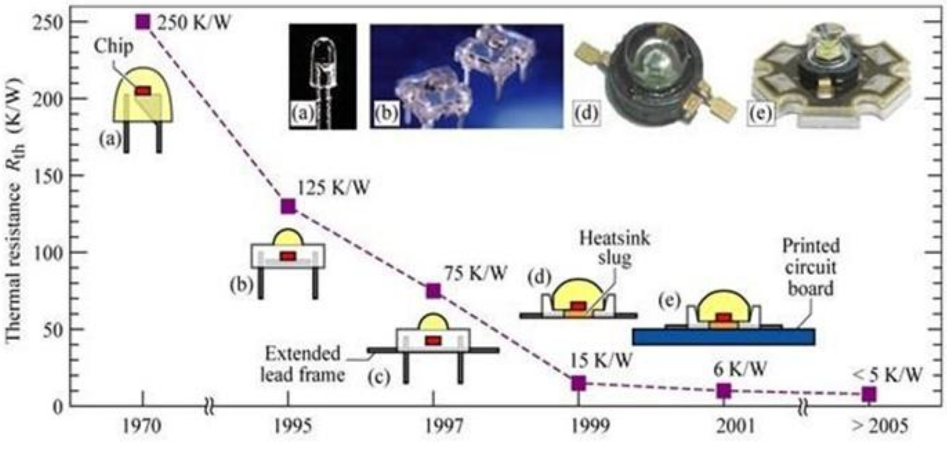
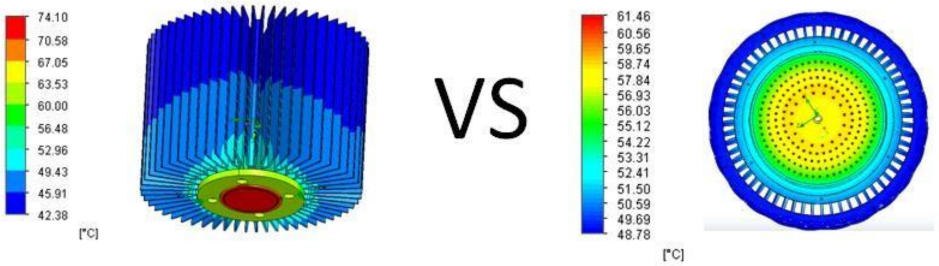


Fig. 30 Thermal Resistance of LED Packages 5 mm, Superflux, Superflux Extended, Emitter, Star LEDs



COB Chip, 74 Degree

SMD Chips, 57 Degree

Fig. 31 Temperature Profile Comparison of COB and SMD LED Cluster

27 LIFE AND LUMEN MAINTENANCE

The life of an SSL (Solid State Lighting) system, such as LEDs, is typically defined based on the degradation of lumen output over time. The most common measure used for LEDs is the L_{70} value, which represents the time it takes for the LED to reach 70 percent of its initial lumen output. This method assumes that LED lamps that fail catastrophically will be replaced.

L_{70} is commonly used in general illumination applications where maintaining a high level of light output is important. This value indicates that the LED has experienced a 30 percent loss in lumen output, which may be considered as the end-of-life point.

27.1 Rated Lamp Life

The ranges for typical lamp life in hours for various electric light sources and lamp life versus dimming trends are shown in Fig. 32. All ranges are for full lumen output. Dimming may increase, decrease, or have no effect on lamp life.

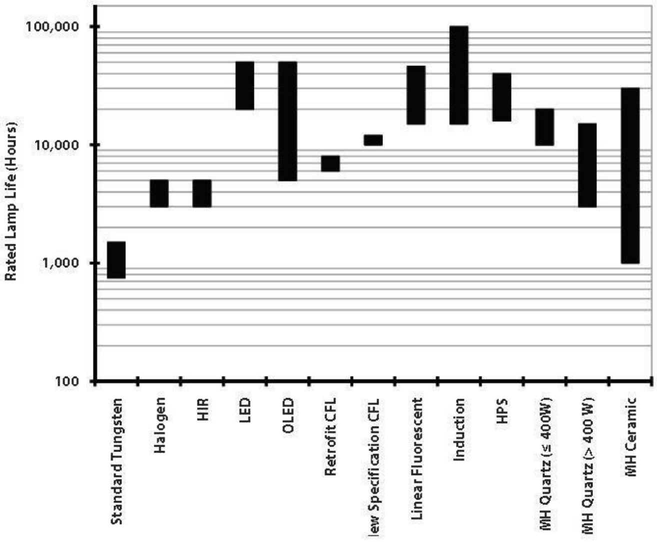


Fig. 32 LED Lifetime Estimate with LM80 and TM-21

LM-80 provides recommendations for testing LED lumen maintenance. This standard outlines procedures for testing the long-term performance of LEDs by measuring their lumen maintenance over a specified period of time. TM-21 prescribes a method for projecting the long-term lumen maintenance of LEDs based on the data collected from LM-80 testing.

LM-80 specifies the test duration, which is typically 6000 hours or 10000 hours. It also originally required a minimum of three case temperatures (55 °C, 85 °C, and 105 °C) to be tested.

27.2 Factors Affecting LED Lifespan

Temperature is indeed a critical factor that significantly affects the useful lifetime of an LED. Excessive heat can dramatically reduce the lifespan of an LED, while proper thermal managementcan help maintain optimal performance and longevity.

To prevent the LED chip from operating at high temperatures, several elements can be incorporated into the design:

a) *Heat sinks or heat spreaders* — These components help dissipate heat away from the LED chip byproviding a larger surface area for heat transfer. Heat sinks are typically made of materials with high thermal conductivity, such as aluminum or copper, and are designed to efficiently dissipate heat into the surrounding environment.

b) *Thermal interface* materials (TIMs) — TIMs, such as thermal pastes or pads, are used between the LED chip and the heat sink to enhance heat transfer. They fill any air gaps or irregularities betweenthe surfaces, improving thermal conductivity and reducing thermal resistance.

c) *Efficient enclosure* design — The overall design of the luminaire or lighting fixture should facilitateproper airflow and heat dissipation. Well-designed enclosures may include ventilation holes, fins,or other features that promote the efficient removal of heat from the LED and surrounding components.

d) *Thermal management systems* — In some cases, active cooling methods such as fans or liquid cooling systems may be employed to maintain optimal operating temperatures for the LED.

By effectively managing temperature through these measures, the LED chip can be kept within itsrecommended temperature range, maximizing its useful lifetime. It's important to note that even asmall temperature difference, such as a 10 °C variation, can have a significant impact on the LED'slifespan, potentially extending or reducing it by thousands of hours.

Overall, careful consideration of thermal management in LED design and application plays a vitalrole in ensuring the maximum lifespan and optimal performance of the LED.

28 BLUE LIGHT EFFECT ON HUMAN CIRCADIAN RHYTHM

Here are some key points to consider:

a) *Blue light hazard for circadian disruption* — When assessing the potential impact of a light source on circadian rhythm disruption, several factors come into play. These include the intensity of the blue light, duration of exposure, timing of exposure (especially during the evening and night), and the spectral power distribution (SPD) of the light source. These criteria help determine the potential effects on melatonin suppression and circadian regulation.

b) *Blue light hazard for retinal damage* — Evaluating the risk of retinal damage from blue light exposure involves additional factors beyond just color temperature. Parameters such as the size of the light source, intensity per unit area on the retina, and the SPD of the light source play crucial roles. The specific characteristics of the light source and its impact on the retina need to be considered for a comprehensive assessment of potential hazards.

c) *Disability glare and discomfort glare* — It's important to distinguish between disability glare and discomfort glare. Disability glare refers to the glare that impairs visual performance, while discomfort glare is the sensation of glare that causes visual discomfort. Disability glare is not directly linked to the SPD of the light source, as stated in the AMA paper, but discomfort glare can be influenced by short wavelengths, including blue light.

d) *Color temperature and circadian system* — Color temperature alone is not a sufficient measure to determine the impact of a light source on the circadian system and melatonin production. Color temperature provides an indication of the warmth or coolness of light, but it does not provide complete information about the SPD. For instance, certain 3000K LEDs may have a greater impact on the circadian system and melatonin suppression compared to some 4000K LEDs if their SPDs contain a significant amount of blue light.

In summary, assessing the effects of blue light on human health and well-being requires considering various factors beyond color temperature. The intensity, duration, timing of exposure, and the SPD of the light source are critical factors to evaluate potential hazards related to circadian disruption and retinal damage. Complete spectral information is essential to make informed decisions about lighting design and minimize potential risks associated with blue light exposure.

29 REDUCING POTENTIAL IMPACT FROM SHORT-WAVELENGTH CONTENT

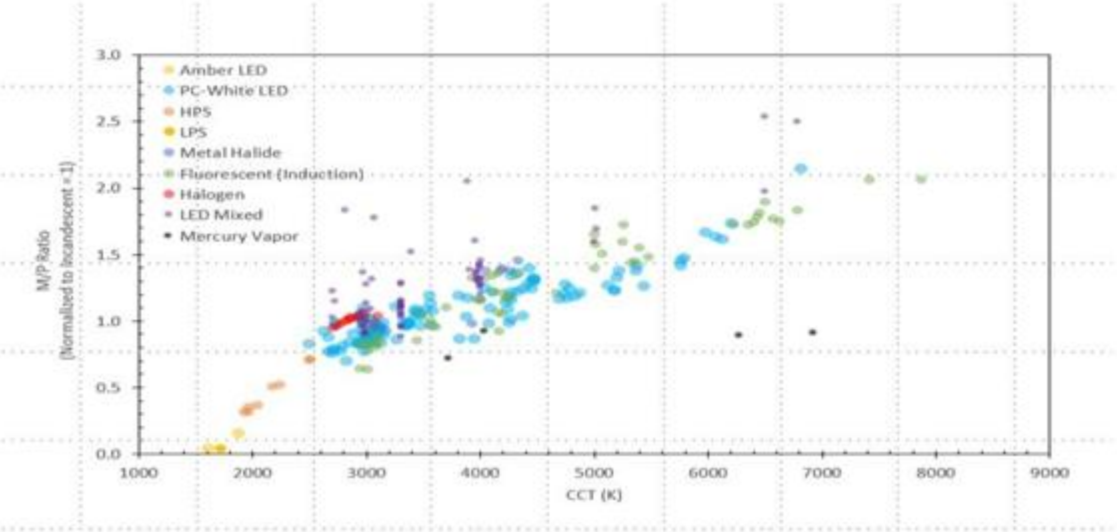


Fig. 33 Melanopic Content and CCT of Various Light Sources

Highlighted some important points regarding the reduction of the blue spectrum content in lighting. Indeed, there are multiple approaches to achieve this, including replacing the lamp with a lower correlated color temperature (CCT) or dimming the light output. Both methods can contribute to reducing the melanopic content (*see* Fig. 33), which has implications for human circadian rhythmand visual comfort. Refer Part 11.

Substituting a higher CCT LED with a lower CCT LED is a straight forward approach to reduce the blue spectrum content. By replacing a 4000K LED with a 3000K LED, there is an averaged reduction in melanopic content of 11.5 percent. This reduction is achieved by considering the specific spectral power distribution (SPD) of each LED. It's important to note that the actual reduction in melanopic content will depend on the SPD of the new light source.

Dimming the lights offers additional advantages in addition to reducing the blue spectrum content:

a) *Reduction in energy use and cost* — Dimming the light output of a luminaire directly reduces energy consumption. By dimming the lights by a certain percentage, energy use is correspondinglyreduced, leading to cost savings in operation.

b) *Longer product life* — Dimming the lights can extend the lifespan of the LED luminaire. Operatingthe LEDs at a lower output reduces the stress on the components, potentially resulting in longer product life and reduced maintenance needs.

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January 2025

Draft National Lighting Code of India

Part 3 Electric Light Sources and Their Accessories

Section 2 LED Driver and Controls

(First Revision of SP 72 Part 3 /Sec 2)

FOREWORD

In recent years, lighting technology has undergone a significant transformation, with traditional filament and discharge lamps being replaced by LEDs (light-emitting diodes) in a wide range of applications. LEDs have become essential to modern lighting systems, and they rely on LED drivers to function effectively. Often referred to as the 'heart' of the lighting system, the LED driver plays a crucial role in ensuring optimal LED performance.

LED drivers are electronic devices that use semiconductors to regulate and supply direct current (d.c.) power, ensuring the proper start-up and operation of LEDs. As energy efficiency regulations have become stricter, many people are increasingly aware of the long lifespan and energy-saving advantages of LEDs. However, it’s important to remember that these advanced light sources require specialized components—LED drivers—to function effectively. Often referred to as LED power supplies, LED drivers serve a role similar to that of ballasts for fluorescent lamps or transformers for low-voltage bulbs. They provide the necessary electrical power to LEDs, enabling optimal performance and reliability.

In the field of digital addressable lighting, DALI (Digital Addressable Lighting Interface) systems integrate both LED drivers and controllers. DALI is widely adopted in both traditional and LED lighting applications, offering enhanced control and flexibility for lighting installations.

Ultimately, LED drivers are vital components in modern lighting systems, ensuring the efficient operation and optimal performance of LEDs, and facilitating the creation of energy-efficient, long-lasting lighting solutions.

Draft National Lighting Code of India

PART 3 ELECTRIC LIGHT SOURCES AND THEIR ACCESSORIES
SECTION 2 LED DRIVER AND CONTROLS

(First Revision)

1 SCOPE

This section of the code (Part 3/ Sec 2) covers an introduction to LED drivers, covering their basic principles, types, operating characteristics, classifications, specifications, and applications, with a focus on general lighting. It also discusses DALI controls in relation to LED drivers (excluding other digital control methods), to help understand the operation of these drivers in LED devices, arrays, or systems.

2 REFERENCE

The standards listed in Annex A contain provisions, which through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of these standards.

3 TERMINOLOGY

3.1 Ballast

Big coil used for conventional HID and TL lighting.

3.2 Controllable Driver/Ballast

Driver/ballast that controls, manages commands, directs or regulates the behaviour though power delivered to a light source between a minimum/off value and a maximum value according to a signal on its control terminals PWM, DALI, 1-10V, etc.

3.3 Converter

DC-DC converter or AC-AC most times input is higher or lower than the output.

3.4 CC

A constant current LED driver maintains a steady output LED current at different LED voltages. This provides the optimum operation for LEDs to reach the possible long life.

3.5 CV

A constant voltage supply will regulate a certain output voltage. Not used for direct connecting LEDs.

3.6 Electronic Transformer

Electronic HF circuit with small transformer inside.

3.7 Efficiency (%)

The efficiency is the ratio between output power and input power. High efficiency is hard to get at low output power, because the fixed losses (to make the desired function) are dominant. $\eta = P_{out} / P_{in}$.

3.8 Electronic ballast

Electronic circuit used for HID and TL lighting.

3.9 Inverter

DC-AC converter.

3.10 Isolated Driver

Driver with isolated output from the supply mains by means such as a safety isolating transformer or converter with separate windings.

3.11 LED Driver

Electronic circuit that converts the mains into the right voltage and current for the LED module.

3.12 MCB

Miniature Circuit Breaker: rated current not more than 100 A. 16A type B often used. Many different classifications of circuit breakers can be made, based on their features such asvoltage class, construction type, interrupting type, and structural features.

3.12 Non-Isolated Driver

Driver with no isolated output. It contains conductive parts which may cause an electric shock in normal use.

3.13 Power Factor (PF = cos φ)

The Power Factor (0 - 1) is the ratio between real power and apparent power.

This unitless value describes how much the current is in phase with the voltage. An ideal resistor load has a power factor of 1.

PF ($\cos \varphi$) = Real Power / Apparent Power

In fact for a non linear load the power factor is a combination of displacement power factor and distortion power factor. The relation can best be described as follows:

$$pf_{true} \leq pf_{displacement} = \frac{1}{\sqrt{1+\left(\frac{THD_I}{100}\right)^2}}$$

3.14 Transformer

Voltage transformer, Current transformer.

3.15 THD_I (%)

Total Harmonic Distortion (0 - 100 percent) of the driver input current.

It is a measure of how close the current waveform is to a pure sine wave. The THD of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

3.16 T Case (°C)

Temperature at a certain test point on the driver casing. When this test point has reached maximum specified T case temperature, the rated lifetime is reduced to 50 percent. A luminaire builder will use this spot to determine the expected lifetime of the luminaire.

4 LED DRIVER

An LED driver (*see* Fig. 1) is the electronic device which regulates the power to LED's. When power flows through LED, holes from the P-region and electrons from N- region are shoot up into the P-N junction. They get mixed with each other to generate photons which is purely visible light. The process of conversion from power to visible light is virtually linear, rise in the power let more electrons and holes mixed in the P-N junction and therefore more visible light is produced.

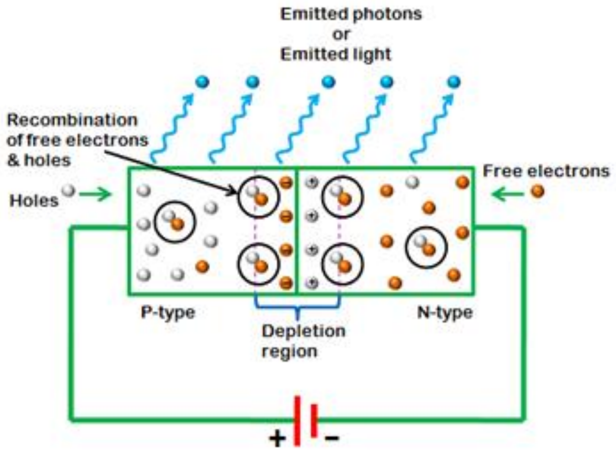


Fig. 1 LED Driver

Conventional lamps used to work on a.c. power directly, LED's operate on d.c. power. If LED's are forced to work on a.c. then It will produce light only when the a.c. signal is in positive half cycle of the a.c. waveform, as LED have polarity.

Below Fig. 2 shows circuit diagram of LED.

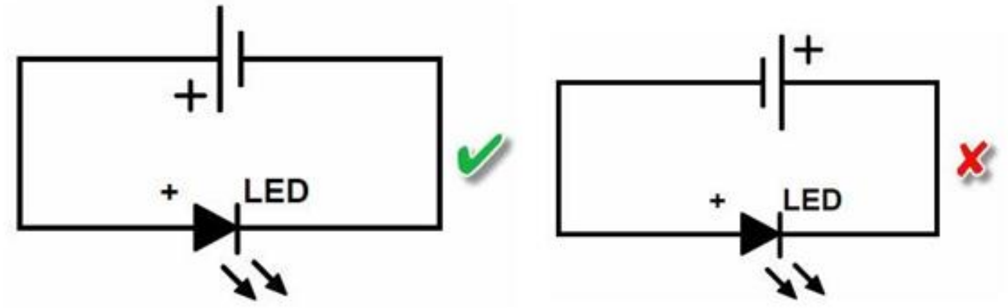


Fig. 2 Circuit Diagram of LED

LED driver act as converter between a.c. power source and LED’s, converting incoming a.c. power 230V, 50Hz to the regulated d.c. power required to drive LED’s. There are drivers designed to takeinputs of other type of power source like d.c. battery and POE (Power Over Ethernet). The LED driver is not just a Power converter. It should handle the voltage fluctuations, noise on the a.c. power and harmonics in the input to avoid unwanted effect in driver output. Any effect in driver output will eventually affect the light output. Latest LED drivers provide additional integrated circuit technology to help the precise control of the light output.

Below Fig. 3 shows LED driver as converter and Fig. 4 shows schematic diagram of LED system

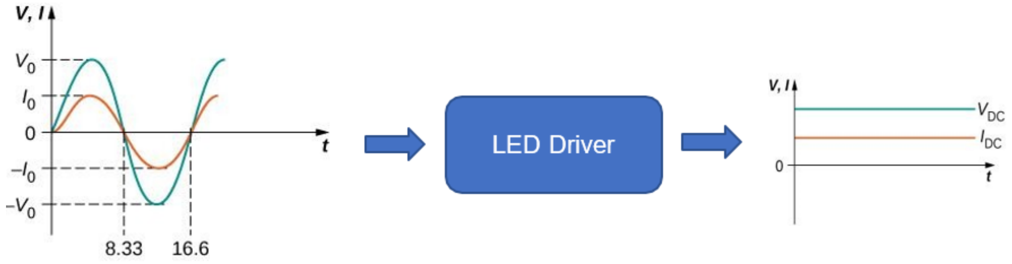


Fig. 3 LED Driver as Converter

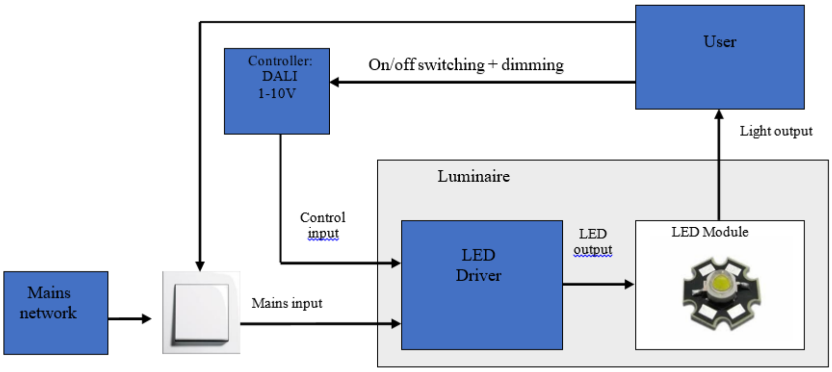


Fig. 4 Schematic Diagram of LED System

In Summary, LED Driver converts High Voltage a.c. current to low voltage d.c. current So that the LED's can be driven with their respective forward voltage and current.

Key Functions of a LED Driver

LED drivers serve several key functions in a lighting system. These functions include:

a) *Voltage and current conversion* — LED drivers are responsible for converting the incomingmains voltage into the appropriate voltage and current levels required by the LED module. This conversion is crucial to ensure that the LED module operates within its specified operating range, preventing any potential breakdown or damage to the LEDs.

b) *Dimming control* — LED drivers often incorporate dimming capabilities, allowing users to control and adjust the brightness or intensity of the LED lighting. This dimming control enables users to regulate the amount of light output according to their needs, providing flexibility in creating desired lighting atmospheres and also helping to save energy by reducing power consumption when lower light levels are sufficient.

c) *Safety and performance optimization* — LED drivers play a vital role in addressing safety and performance issues associated with LED lighting. They are designed to ensureelectrical and mechanical safety, protecting the LEDs and the entire lighting system from potential hazards such as overvoltage, overcurrent, and short circuits. LED drivers also optimize electrical performance by providing stable and consistent power supply to the LEDs, helping to maximize their efficiency and longevity.

By fulfilling these key functions, LED drivers enable the efficient and reliable operation of LED lighting systems, ensuring optimal performance, energy efficiency, and safety. They are an essential component in achieving the benefits of LED technology in various lighting applications.

4.1 Types of LED Driver

An electronic device that converts the incoming power to a constant-voltage d.c. output has been referred to as a Power supply, whereas an LED driver is been denoted to an electronic device thatprovides a constant current d.c. output. Today, "LED driver" and "LED power supply" are very unclear terms that are being used interchangeably. Despite the terminological uncertainty, we can'tafford to neglect the basic differences between the constant current (CC) and constant voltage (CV) circuits.

4.1.1 *Constant Current LED Driver*

Constant current LED drivers (*see* Fig. 5) deliver a constant current (For example, 350mA, 500mA, 700mA, or 1A), irrespective of the load voltage, to an LED module within a specific voltage range.

The CC LED driver can drive a single module with LEDs connected in series or multiple LED modules connected in parallel. Series connection is preferred in CC circuit because it ensures all the LEDs have the same current flowing across their semiconductor junctions and the light outputis unvarying across the LEDs. However, this limits the no. of LED’s can drive on single driver output.

Fig. 5 Constant Current LED Driver

Constant current LED drivers are used when light output should be independent of the input voltage fluctuation. They are mainly used in lighting products such as down lights, linear profiles,table/floor lamps, pendants, street and high bay lights. These Lighting products require precise constant current output from LED driver.

CC drivers support both pulse-width modulation (PWM) and constant-current reduction (CCR) dimming. Operating a power supply in a CC mode usually requires overvoltage protection just incase an excessive load resistance is encountered or when the load is disconnected.

4.1.2 *Constant Voltage LED Driver*

Constant voltage LED drivers (*see* Fig. 6) are designed to drive LED’s at a fixed voltage, typically 12V or 24V.

It is generally preferred to provide a constant voltage supply to multiple LED modules or string ofLED’s connected in parallel. Parallel connection is preferred in CV circuits because it ensures allthe LEDs have the same voltage flowing across their semiconductor junctions.

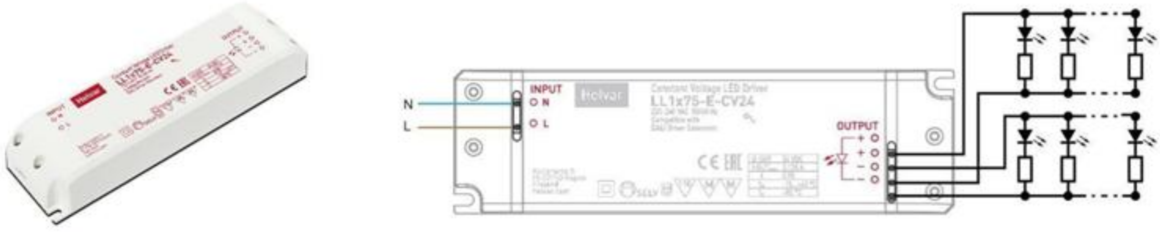


Fig. 6 Constant Voltage LED Driver

CV drivers are often used in low voltage LED lighting applications that requires large no. of smallpower LED’s to be connected to a single driver output. For example LED strip lights, LED signages. Constant voltage drivers can only be PWM dimmed.

The CV driver must sustain the power dissipation when the load goes short circuit. The current limiters typically have thermal shutdown to protect the circuit when a voltage higher than the max.Suitable voltage is placed across the current limiter.

4.1.3 *AC LED Driver*

The purpose of a.c. LED driver (*see* Fig. 7) is to convert 230V a.c. voltage to 12/24 V d.c. Voltage. Mainly used to power the internal driver of retrofit LED lamp. The Internal driver of LED lamp will convert the low voltage a.c. to desired d.c. voltage.

Fig.7 AC LED Driver

4.2 Switch Mode Power Supply (SMPS)

As LEDs are very sensitive to current and voltage fluctuations, one of the most important roles ofan LED driver is to decrease variations in forward voltage across the semiconductor junction of the LEDs.

Switched-mode power supplies (*see* Fig. 8) operate by modulating an electrical signal using one or more switching elements such as MOSFETs at a high frequency. Thus generating the fixed magnitude of d.c. power under supply voltage or load variations. Switch-mode converters used in LED driversrequire energy to be stored as current using inductors and as voltage using capacitors so as to maintain the output current or voltage on the load during the on/off switching cycle. An a.c.-d.c. SMPS LED driver rectifies a.c. power into d.c. power which is then converted into d.c. power capable of driving the LEDs.

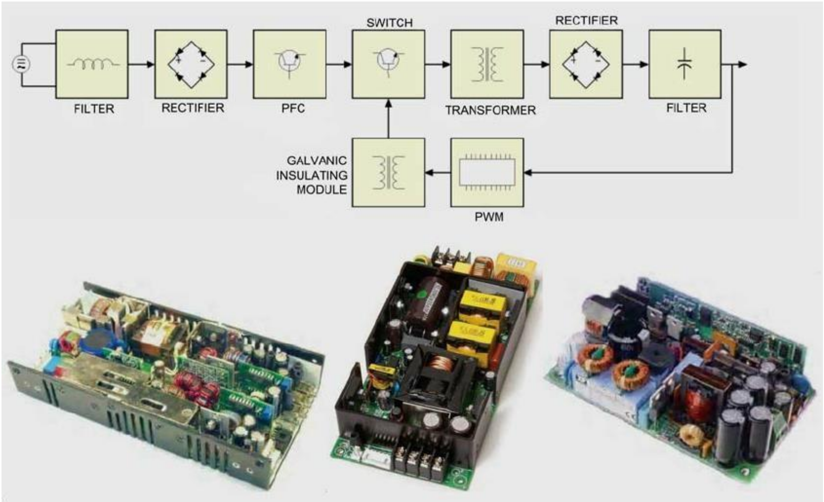


Fig. 8 Switch Mode Power Supply

For the switched-mode power conversion in LED drivers, various circuit topologies are available to support the LED load requirements. Among all SMPS topologies, buck boost, buck-boost, and flyback are the most commonly used types.

4.2.1 *Buck Circuit Topology*

Also known as a step-down converter, a buck circuit regulates input d.c. voltage down to a desired d.c. voltage using a number of current control methods, including synchronous switching, hysteretic control, peak current control, and average current control. The buck topology is designed for mains-powered LED drivers which are required to drive a long string of LEDs, with the load voltage kept under the supply voltage. Buck circuits are also frequently found in low voltage applications where the input supply voltage is relatively low (For example, 12 VDC for automotive lighting) and just one LED is being driven.

Below Fig. 9 shows buck circuit.

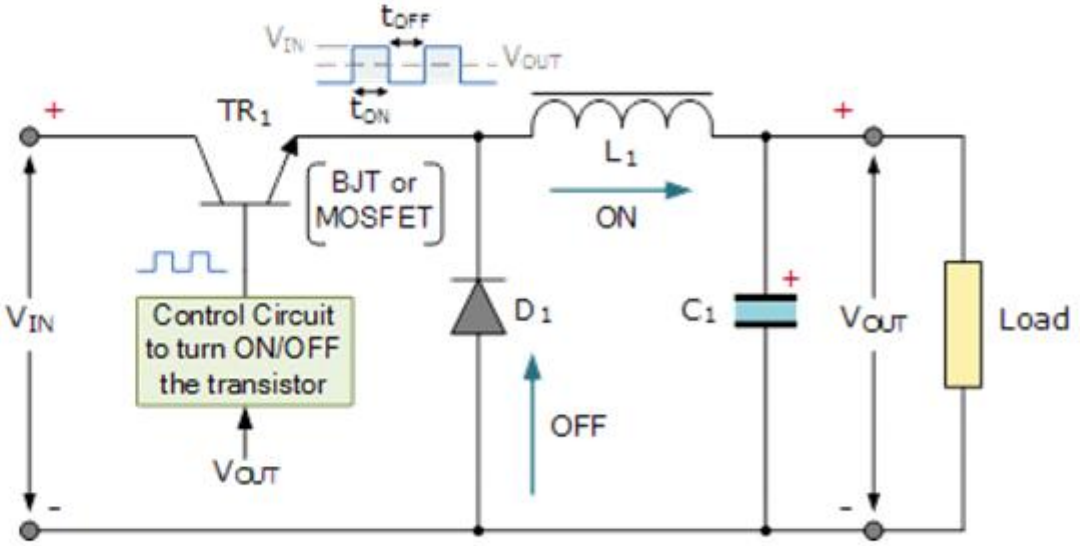


Fig. 9 Buck Circuit

The buck topology allows for circuit design with fewer component counts while maintaining a high efficiency (90–95 percent). However, the load voltage of a buck circuit must be less than 85 percent of the supply voltage. Moreover, buck LED drivers do not offer isolation between the input and output circuits.

4.2.2 *Boost Circuit Topology*

A boost converter is designed to step up the input voltage to a higher output voltage by about 20 percent or more.

Boost circuits generally require one inductor and operates in either the continuous conduction mode (CCM) or discontinuous conduction mode (DCM), as determined by the waveform of the inductor current.

Low-power boost converters can use a charge pump, rather than an inductor, which uses capacitors and switches to raise the output voltage above the supply voltage. Inductor-based converters offer the advantage of low component counts and high operational efficiencies (greater than 90 percent).

Below Fig. 10 shows boost circuit.

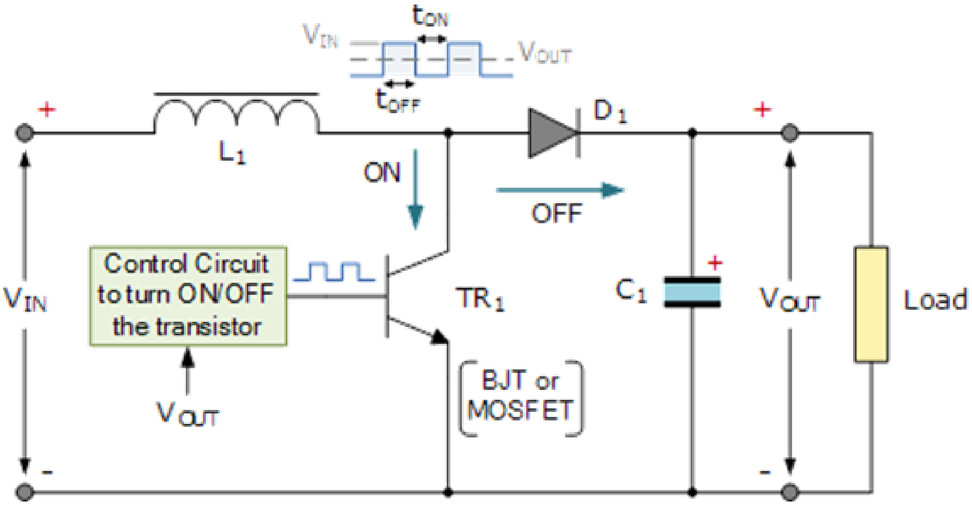


Fig. 10 Boost Circuit

The disadvantage of this topology is that it offers no isolation between the input and output circuits. Boost converter outputs a pulsed waveform and thus requires a large output capacitor to reduce the current ripple. PWM dimming is challenging with the large output capacitor as well as the closed-loop control which demands a large bandwidth to stabilize the converter.

4.2.3 *Buck Boost Topology*

Buck-boost converters can provide an output higher or lower than the input voltage, making them ideal for applications where the input voltage rises and falls with a large variation (no more than 20 percent). Input voltage fluctuations of this type usually occur in battery-powered lighting applications, For example, vehicle-mounted lighting for construction and agricultural machinery (forklifts, tractors, harvesters, diggers, snow ploughs, etc.) as well as trucks and buses.

Below Fig. 11 shows buck boost circuit.

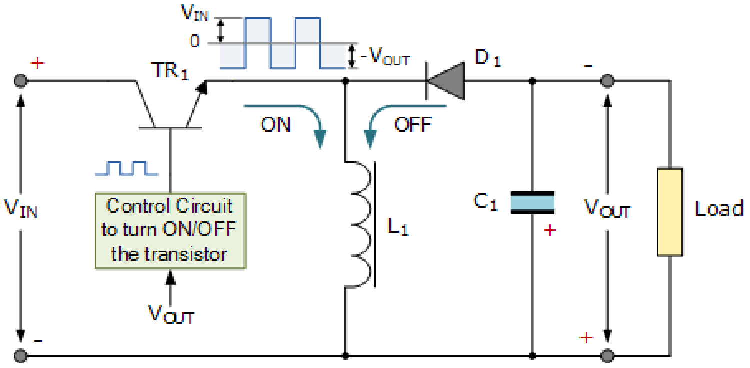


Fig.11 Buck Boost Circuit

Two types of converters often found in buck-boost applications are known as SEPIC (single-endedprimary inductance converter) and Cuk.

The SEPIC converter is characterized by the use of two inductors, preferably a dual-winding inductor which has a small footprint, low leakage inductance, and the ability to increases the coupling of the windings for improved circuit efficiency. In a SEPIC architecture, the boost sectionprovides power factor correction (PFC) and the buck section produces a voltage to be the same as,lower, or higher than the input voltage, while output polarity of both sections remains the same. Below Fig. 12 shows SEPIC Architecture.

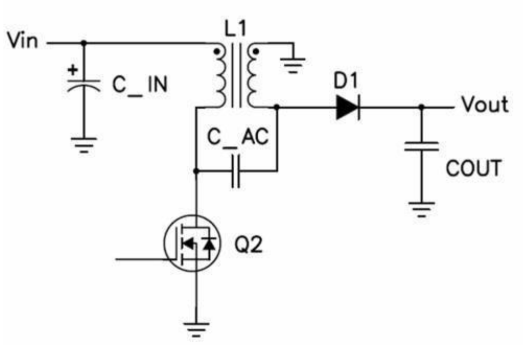


Fig.12 SEPIC Architecture

The Cuk topology combines the continuous output current of a buck and the continuous input current of a boost, which gives the Cuk the best EMI performance and allows the capacitance to be reduced as needed. The buck-boost converter is a non-isolated driver circuit. Like boost converters, buck-boost converters require overvoltage protection to prevent damages from excessively high voltage in case of an open-load condition.

4.2.4 *Flyback Switching Topology*

A flyback switching circuit (*see* Fig. 13) is a discontinuous conduction mode converter which provides a.c. mains isolation, energy storage, and voltage scaling. It is very much like a buck-boost converter, but with the inductor split to form a transformer.

The flyback transformer with at least two windings not only provides complete isolation between its input and output circuits, but also allows for more than one output voltage in different polarities. The primary winding is connected to the input power supply, the secondary winding is connected to the load. Magnetic energy is stored in the transformer while switch is on and at the same time the diode is reverse-biased (for example blocked). When the switch is off, the diode is forward-biased and magnetic energy is released by current flowing out of the secondary winding. Some flyback circuits use a third winding, called a bootstrap or auxiliary winding, to power the control IC.

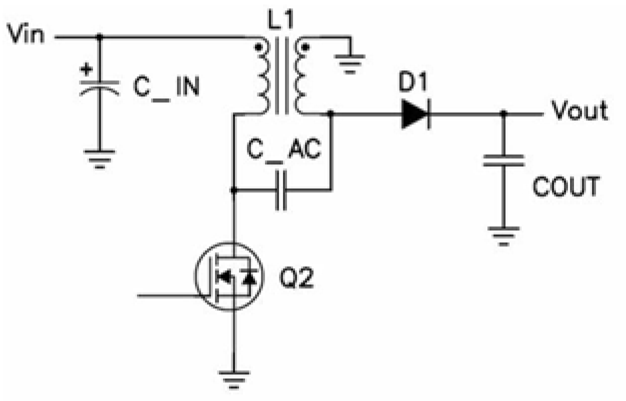


Fig.13 Flyback Switching Circuit

More accurate control of the average voltage across the capacitor, which is used to maintain currentflow in the LED load when the converter is on the first step, requires isolated feedback, usually via an optocoupler. Flyback switching circuits can be designed for a very wide range of supply andoutput voltages, with isolation from dangerously high voltages. However, these circuits are less efficient (75 – 85 percent, higher efficiency is possible by using expensive parts).

4.3 Linear Power Supply

A linear power supply (*see* Fig. 14) uses a control element (such as a resistive load) which operates in its linearregion to regulate the output. In this type of LED driving circuits, the voltage flowing through a current-sensing resistor is compared to the voltage reference in a feedback loop to produce the control signal. A controller which is operated in a linear region of the closed loop feedback systemadjusts the output voltage until the current flowing through the sensing resistor matches the feedback voltage. The current delivered to an LED string is thus maintained if the forward voltagedoes not exceed the dropout-limited output voltage.

Linear drivers provide only step-down conversion, which means the load voltage must be kept lower than the supply voltage. If the load voltage is higher than the supply voltage or the supply voltage has a wide variation, a switching regulator is needed.

AC mains-powered applications, which has demanding requirement for voltage regulation, typically choose switched linear regulators to drive LED lamps with a long string of LEDs wired in series. Switched linear regulators are combinations of multiple linear regulators which are eitherintegrated or cascaded in a modular form. Typically designed in surface-mount IC packages, theselinear regulators are used to intelligently adjust the number of loads connected LEDs in a string during a power line cycle so that the load voltage matches the instantaneous a.c. mains voltage.

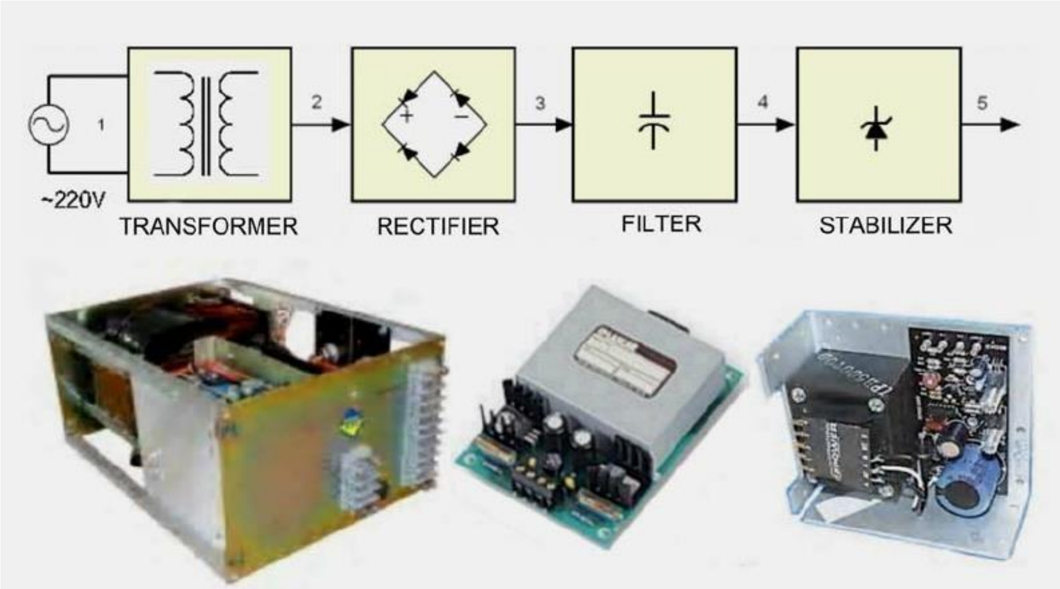


Fig. 14 Linear Power Supply

4.3.1 *Switch Vs Linear*

Designing an LED driver involves multiple factors. Choosing between SMPS and linear drivers requires consideration of cost, efficiency, control, lifespan, dimming capabilities, size, power factor, flicker, input/output requirements, a.c. mains isolation, and other relevant factors.

Switching Mode Power Supplies (SMPS) are highly efficient due to their ON/OFF switching modulation. They offer features like high power efficiency, flicker-free illumination, and digital control, making them ideal for IoT applications. However, their dependence on reactive components like transformers and capacitors, coupled with high-speed switching, introduces challenges such as increased cost, electromagnetic interference (EMI), and reduced reliability due to capacitor degradation.

Linear LED drivers, while simpler and more reliable, were traditionally less efficient. Recent advancements have improved their conversion efficiency and flicker performance, making them a viable choice for applications requiring high-quality light, electrical safety, and flicker-free operation. Linear drivers also reduce costs and simplify lamp design, making them a preferred solution in specific scenarios.

4.4 Driver on Board (DOB)

DOB is a typical implementation of the linear driving topology. Also called an a.c. LED light engine, the DOB LED module accommodates the LEDs and all the driver electronics on a metal- core printed circuited board (MCPCB). DOB technology takes advantage of the MCPCB- mountability of the high voltage driver ICs (switched linear regulators).

Unlike the SMPS driver circuitry which has to be mounted on a routed FR4 PCB, these surface-mount driver ICs can be soldered to the LED-mounted MCPCB without circuit routing. This eliminates entirely the need for a dedicated driver assembly and thus allows for a compact form factor.

Another benefit of DOB design is that the excellent thermal conductivity of the MCPCB can facilitate rapid dissipation of heat generated due to the inefficient conversion of a linear driver.

Below Fig. 15 shows driver.

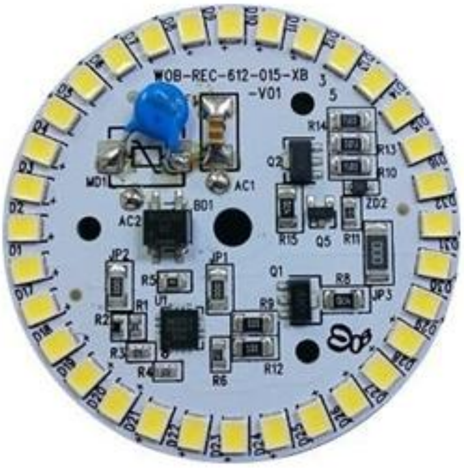


Fig.15 Driver

4.5 Emergency LED Driver

In the event of power failure, the lights should never go off completely. For that reason, LED drivers are equipped with builtin emergency battery and named as Emergency LED drivers. These drivers can work on both a.c. as well as d.c. input supply. During times when the mains power is on, the driver takes input supply from mains power (a.c.) and when the mains power is OFF, the drivers takes input supply from the battery. The battery is constantly restoring the charge in an ideal mode and release the chargein the event of mains power failure.

The battery should be maintenance free, quick charged within 24 h and provide back up of min 1 h to 3 h of duration.

5 TYPES OF DIMMABLE LED DRIVERS

The evolution from traditional lamps to LED's is obsessed by the need for better energy efficiency,control and communication. One of the benefits of LEDs is the ability to respond instantly to changes in power input which is regulated by the LED driver.

Also, the price of LED is speedily decreasing despite the fact their efficacy is increasing day by day. Their efficacy is now competitive to conventional fluorescent lamps.

Nevertheless, the Lifespan of LED's is significantly longer than 1,00,000 burning hours, Dimming LED's will further extend their Life span. As Dimming the LED's produces less heat, meaning lower junction temperature. In general, the lower the junction temperature, higher is the lifespan. The non-dimmable LED drivers deliver constant light output throughout the operation and one cannot change the light output at desired level. However, the dimmable LED drivers offer the flexibility to user to regulate the light output from 100 percent to 1 percent or even less. The dimming performance of LED drivers is extremely important as lighting becomes more connected and adaptive towards user's need and mood.

The dimming methods are continuously evolving from conventional TRIAC dimming to latest DALI dimming.

5.1 TRIAC Dimming

TRIAC (Triode for Alternating current) is a bidirectional thyristor device which can be used as a switch to conduct current in both positive and negative cycles of a.c. waveform. TRIAC dimmers fundamentally cuts the incoming a.c. mains Voltage to reduce the average value of the Output Voltage. Also known as Phase Control dimmers.

They are further categorised as Leading Edge and Trailing Edge Dimmers. The leading-Edge dimmer cuts down the part of a.c. waveform at the leading edge of a.c. waveform whereas the trailing dimmers cut down the part of a.c. waveform at the trailing edge of a.c. waveform. These were first designed to control electronic low voltage transformers (ELV). Below Fig. 16 shows TRIAC dimming graph.

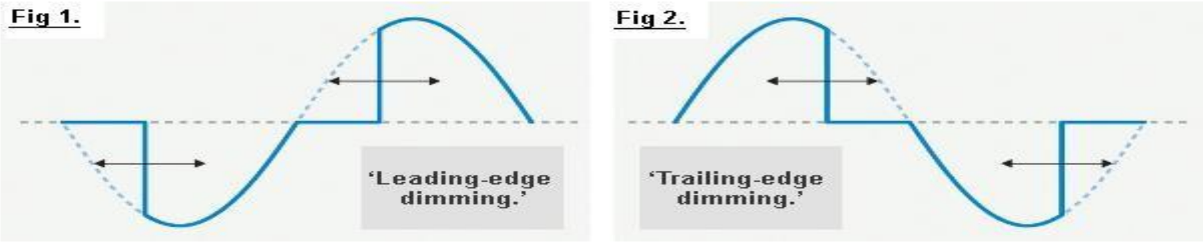


Fig. 16 TRIAC Dimming Graph

Though TRIAC dimmers have an advantage of simplest dimming method and easy on installation, it also leads to distorted input voltage to LED drivers. Resulting in low power factor and higher harmonic distortion. LED drivers are reactive loads to the dimmer, which states that LED driverswill distort the incoming a.c. mains supply extremely by operating on nonlinear supply. They alsopresent the zero-load condition at every a.c. waveform. This kind of zero-load condition make thedimmer operation to go wrong and creating flicker in light output. Except the control LED drivers which are designed to detect and react to the input supply in desired way. For an LED driver to react correctly, it is essential to add numerous vital blocks like sensors which can monitor the a.c. supply waveform before the power factor correction stage.

In summary, TRIAC dimming is not ideal for dimming LED load and often results in limited dimming range, flickering, blinking and colour shifting of LEDs over the period. It's habitually used in retrofit applications where drawing additional control wiring is difficult and expensive.

5.2 0-10V / 1-10V / Analog Dimming

0-10V or Analog Dimming works on the small voltage (between 1-10V d.c.) control signal throughextra pair of control wiring between dimmer and LED driver. These drivers dimmed from 100 percent (10V) to 10 percent (1V) to 0 percent (0V) means off.

Below Fig. 17 shows analog dimming curve.

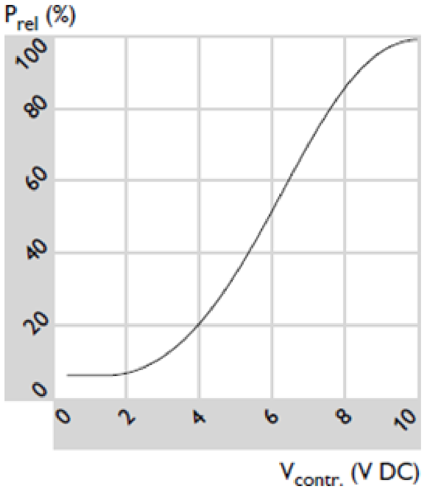


Fig. 17 Analog Dimming Curve

Below Fig. 18 shows schematic diagram of analog dimming.

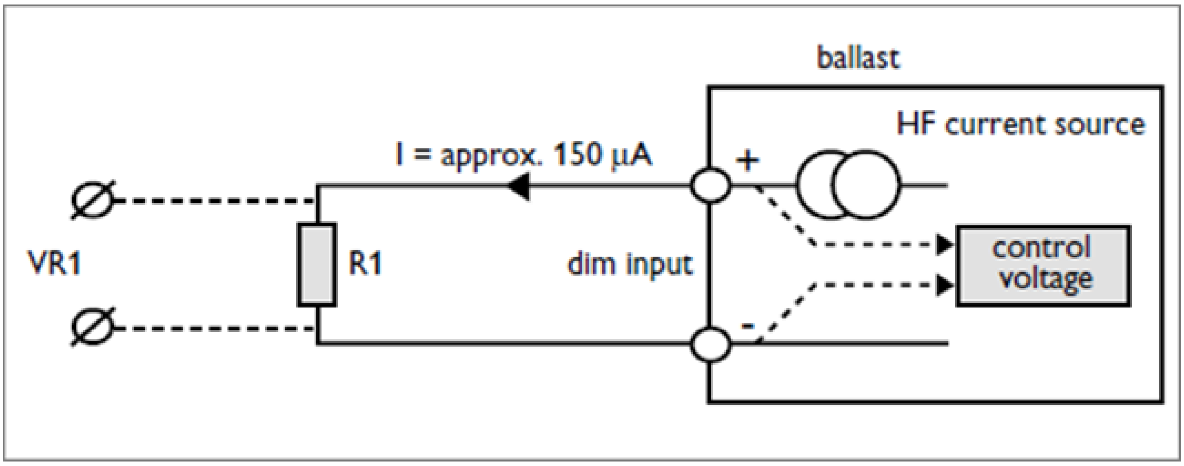


Fig. 18 Functionality Schematic Diagram of Analog Dimming

These are further categorized into current sourcing and current sinking types. Sourcing current refers to the ability of the digital output port to supply current. Sinking current refers to the abilityof the port to receive current. If the control input is not connected, the unit is in the 100 percent light position.

If the control input is short-circuited the setting is at minimum lighting level. An external control voltage is not necessary. By inserting a potentiometer, continuous regulation can be achieved in a simple way. The control current that can be delivered by the driver is 0.15 mA.

The current source dimming is a front-end (user driven) method of lighting control intended for theatrical and entertainment applications.

Whereas the current sink method, a back-end protocol designed for architectural lighting fixtures. In this method, the LED driver is the current source for the d.c. signal and the dimmer is the point of reference. The driver associates the input voltage, which is adjusted by varying the voltage between 1 V (minimum level signal) and 10 V (maximum light), to a dimmed load. When these two control wires are open, the driver receives a 10V dimming signal and outputs 100 percent of the rated load. When the control wires are shorted together, the driver receives a 0V dimming signal and the output of the driver will be set to the minimum. If a level of 60 percent is set, the dimmer would sink the signal voltage to 6V. This method is also known as 1-10V dimming since 1 volt is the minimal level signal, and 0V turns the lamp off as the driver will drop in to sleep mode. Most 0-10V dimmable drivers dim from 100 percent to 10 percent apparent output.

Unlike phase control dimmers which cut power in the line voltage to the fixture, 0-10V dimming occurs in the driver and thus no heat is generated in the dimmer and transmitted across the wires. This attribute allows 0-10V dimmable LED drivers to control larger loads. The low voltage control wires are polarity sensitive. Long wire runs can cause a signal level drop, resulting in non-uniform light output from light fixtures which are operated by different drivers and control LED by the same control device.

Also adjusting the 0-10V signal with dimmers from different manufacturers will not necessarily achieve uniform dimming across different LED luminaires. Poor compatibility among dimmers and drivers can present a new level of challenges.

5.3 Digital Dimming

A digital signal is connected to the LED driver to provide dimming. The common form of digital dimming is PWM and DALI.

5.3.1 *PWM Dimming*

Pulse-width modulation (PWM) switches the LED current at a high frequency between 0 and the rated output current to adjust LED brightness. PWM dimming depends on the human eye's abilityto assimilate the average amount of light in the pulses, also a digital dimming. The perceived brightness is approximately proportional to the duty cycle of the pulses (the ratio of the on-time and off-time). The continuous stream of pulses is modulated at a frequency high enough to be imperceptible to the human eye or even to high speed video cameras. Pulse-width modulation dimming can be used for LED arrays that run off either constant voltage (CV) drivers or constantcurrent (CC) drivers.

A PWM driver will only operate the LEDs at the rated forward current level or zero. As such, the CCT of the LEDs is maintained throughout the dimming range. The consistent CCT simplifies thecolor mixing process. Since the LEDs are always on at the same current level, a very precise output level can be achieved. All these advantages make PWM dimming particularly viable for RGB fullcolor tuning applications. PWM is also an energy efficient current modulation method because it periodically switches between a full-amplitude current and a zero current thus reducing the runningtime of the LEDs.

The primary disadvantage of PWM dimming is that high frequency switching can generate electromagnetic interference (EMI) and audible noise. In addition, PWM drivers cannot be remotemounted as the changes in capacitance and induction owing to increased transmission distance canend up in interference with high frequency control. Fig. 19 shows PWM Dimming.

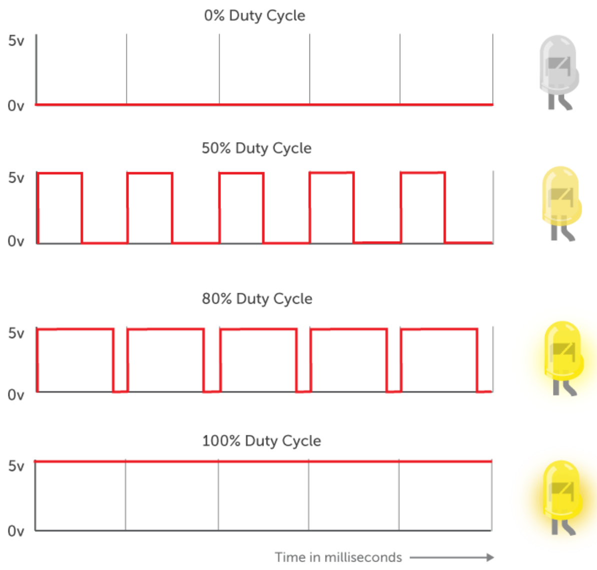


Fig. 19 PWM Dimming

5.3.2 *Digital Addressable Lighting Interface (DALI) Dimming*

DALI was created to provide central control of light fixtures over a single pair of wires which operates at approximately 16VDC and carries a digital signal from a DALI controller to an LED driver. The other two wires provide a constant line voltage to the driver. This interface protocol for digital communication allows addressing, grouping, and dimming of up to 64 light fixtures andcontrol devices. Its ability to communicate with the light fixtures individually, collectively or in groups via bi-directional data exchange provides great flexibility for light management. A DALI system can digitally assign occupancy sensors, photocells, time clocks, and other control devices to one or many fixtures without complicated wiring. DALI addresses the need for multilayer lighting control which requires light fixtures to respond to more than one controller and to be assigned to more than one control zones simultaneously.

The protocol uses logarithmic dimming with the curve matched to the sensitivity of the eye. DALIdimming technology uses 8-bit resolution for 254 individual steps, allowing users to obtain very precise output control with a dimming range of 0.1 percent to 100 percent.

DALI control lines have no polarity, which provides simplicity of installation. The DALI system uses a balanced pair of wires as the control bus and Manchester encoding for data-modulation. Therefore, the digital signal is immune to external interference, all light fixtures in a DALI lightingsystem can be uniformly dimmed.

The IEC 62386 standard (*see* Fig. 20) was restructured in late 2014 for ease of use, and many improvements were made including the addition of new commands and features.

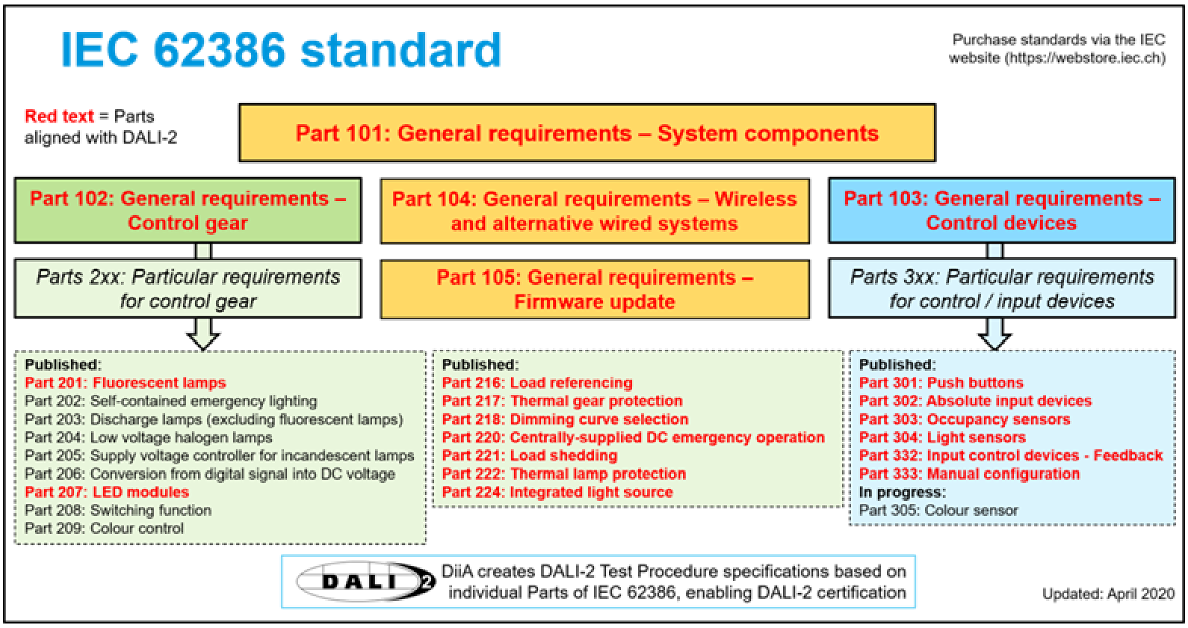


Fig. 20 IEC 62386

With the latest innovations into DALI dimming protocol, DALI dimmable drivers are further categorizing into DALI1, DALI 2, DALI 8 and D4i.

5.4 DMX Dimming

DMX or DMX512 originally developed for entertainment and stage lighting applications, is nowwidely used into interior and exterior architectural spaces. DMX employs EIA-485 (RS-485) differential signaling at its two-wire physical layer. This variable-size, packet-based communication protocol has a transmission rate of 250 kBit/s. The unidirectional, channel-based protocol streams data continuously in a sequenceof up to 512 data frames (slots) for up to 512 channels. Each DMX512 dimming channel controlsone recipient and transmits data in 8 bits giving 256 steps of color depth. DMX is typically used to control RGB LEDs, which takes up three channels from the DMX512 stream to control one triplet. Data is transmitted over a cat 5 or 3-core shielded cable which is polarity dependent.

5.5 Switch Dimming

With switch DIM it is possible to create lighting systems that can be easily switched and dimmedat low cost. The key is simple but clever. It involves using standard mains voltage switches for lighting control. The different switching and dimming functions are performed depending on the operating status at the time and how long the switch is pressed. A short press on the switch switchesthe connected ballasts on or off; holding down the switch will fade the connected ballasts up or down.

Below Fig. 21 shows switch dimming.

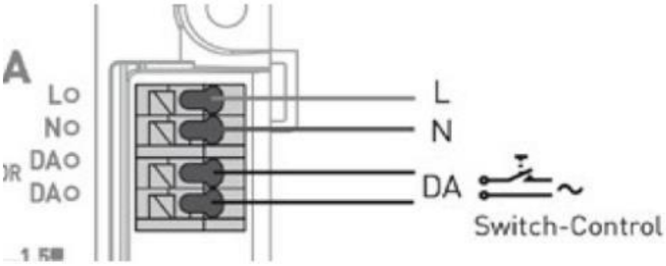


Fig. 21 Switch Dimming

6 SETTING UP DRIVER OUTPUT AND VARIOUS OTHER PARAMETERS

6.1 Setting Driver Output

Nowadays, the output of the latest LED driver can be set with the help of Current Limiting resistoror Dip Switch selection on board.

6.1.1 The LED-I_{set} resistor/current setting values are adjusted according to the LED set specification. The resistor value for each required output current can thus be calculated from the formula R [Ω] = (5 [V] / I_{out} [A]) * 1000. Below Fig. 22 is the example LED-I_{set} resistors and Fig. 23 explains the data of LED-I_{set} resistors.

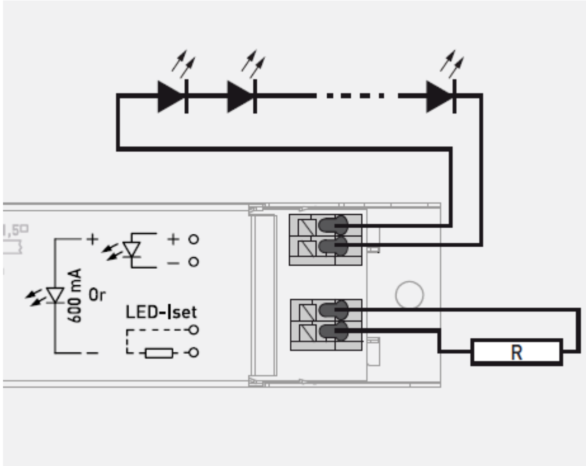


Fig. 22 LED-I_{set} resistors.

LED-Iset resistor model	MAX	800 mA	750 mA	700 mA	650 mA	600 mA	550 mA	500 mA	450 mA	400 mA	350 mA	300 mA	No resistor
I_{out} (mA)	850	800	750	700	650	600	550	500	450	400	350	300	250
Order code	T90000	T90800	T90750	T90700	T90650	T90600	T90550	T90500	T90450	T90400	T90350	T90300	N/A
Resistance values (Ω)	0	6.2k	6.65k	7.15k	7.68k	8.25k	9.09k	10k	11k	12.4k	14.3k	16.5k	∞

Fig. 23 LED-I_{set} Resistors Data (Current, Order Code and Resistance Value)

The current can be adjusted also with normal resistors by selecting suitable resistor value (formulaR [Ω] = (5 [V] / I_{out} [A]) * 1000). Reference resistor values are given in Fig. 23.

6.1.2 The current can also be set with dip-switches. With each combination of switch setup, a different output current value can be set. The maximum value can be reached with all switches setto "1" (pushed downwards, away from the connectors.

7 INDOOR AND OUTDOOR DRIVERS AND THEIR APPLICATIONS GUIDELINE

7.1 Classifications

The electronic driver portfolio can be divided in a range dedicated for indoor application and the other range is specially developed for outdoor use. The major differences between indoor and outdoor applications are:

a) Risk due to salts, chlorides or other air contaminations (near sea, tunnels);
b) Risk of lightning strokes (high poles in open field);
c) Risk due to humidity/moisture in the driver;
d) Risk for strong bumps and/or vibrations (high poles, close to heavy traffic, bridges); and
e) Risk due to strong mains distortions, voltage spikes, and surges.

Below, Table 1 is an overview of requirements when using Indoor and Outdoor drivers:

Table 1 Overview of Requirements When Using Indoor and Outdoor Drivers
(*Clause* 7.1**)**

Sl No. (1)	**Requirements** (2)	**Indoor Products** (3)	**Outdoor Products** (4)
i)	Air contaminations	No protection needed	Protection needed against exhaust gasses (chlorides) and salts
ii)	EMC-V surge	IS 14700 (Part 4/Sec 5) Installation class 3*) 2kVL/N – Ground 1kV L-N	IS 14700 (Part 4/Sec 5) Installation class 4*) 6-10 kV L/N – Ground (common mode) 4-8 kV L-N (differential mode)
iii)	Vibration levels	IEC 60068-2-6-Fc Frequency range 10 - 150Hz. Acceleration/amplitude 2G/0.15mm peak	IEC 60068-2-6-Fc Frequency range 10 - 150 Hz. Acceleration/amplitude 5G/0.15mm peak
iv)	Lifetime	40k-50k hours @ 90 percent survivals	60k-100k hours @ 90 percent survivals
v)	Temperature range luminaire	T_{amb} 0 – 40 °C	T_{amb} 30 – 35 °C
vi)	ESD protection	No special requirements	LED module protection against ESD charging due to wind
vii)	Repair cost	Low	Typically very high per incident

7.2 Using Indoor Drivers in Outdoor Applications Guideline

In practice we see that for some less demanding outdoor applications such as bollards, decorative and architecture lighting successfully indoor drivers are used. Customers sometimes protects the electronics in the luminaires and accepts failures in case of surges because replace cost are relatively low.

Guideline of using different type of driver for different applications.

7.3 Constant Voltage Vs Constant Current

7.3.1 *CC -Constant current LED driver*

A constant current LED driver maintains a steady output LED current at different LED voltages.This provides the optimum operation for LEDs to reach the possible long life.

7.3.2 *CV - Constant voltage supply*

A constant voltage supply will regulate a certain output voltage. Not used for direct connecting LEDs.

8 LED DRIVER MARKING AND RATINGS

8.1 Permanent Marking

Drivers shall be permanently marked per the requirements of the applicable safety standards (IS 15885). The model no of the product should be a part of Label and no stickering is allowed altering the current and voltage rating of driver.

8.2 Rated Supply Voltage Designation Supply (Input) Ratings

The LED driver ratings and markings should include:

a) The maximum nominal input voltage;
b) The maximum input currents;
c) The maximum input powers; and
d) The input frequency (For example 50 Hz).

NOTE — A LED driver with a dynamic input voltage range (For example 120 to 277V) should be marked with the input current at the minimum nominal input voltage and at the maximum nominal input voltage. Any other input current shall be in between these two extreme values.

Additional input information may be provided in the driver manufacturer catalogue and data sheets.

8.3 Output Regulation

Until such time as further marking requirements are specified in standard, the manufacturer in product literature or on the product itself.

8.4 Common Voltage Ratings (Nominal (Input or Supply) Voltage and Frequency)

The preferred design-centre supply-voltage ratings for drivers covered by this standard are 100-300V a.c. at 50Hz.

8.5 LED Load (Array, Module, or Package)

The rated load of a driver shall be specified as noted below:

a) Maximum output wattage of the driver;
b) For drivers that supply a constant voltage, output voltage in volts a.c. or d.c. on the product label;
c) In any collateral publications (instructions, specifications), the output voltage in VDC shall include a tolerance band specified as a percentage (For example, 24 VDC ±5 percent);
d) For drivers that supply a constant current, output current shall be specified in amps on the product label;
e) In any collateral publications (instructions, specifications), the output current in amps shall include a tolerance band specified as a percentage (For example, 5 amps ±5 percent); and
f) For drivers designed to operate specific modules or arrays, those modules and/or arrays shall be specified on the label and/or in the install instructions.

NOTE — The output rating and the maximum output capability are not usually the same.

8.6 LED Driver Operating Temperatures

Drivers are designed to start and operate LED loads over a range of ambient temperatures. Due tovariations of thermal transfer capabilities with fixture designs, the ambient temperature is not always an ideal way to specify product capability while the maximum T_c is a better measurement for application determination. The minimum ambient temperature and the maximum T_c temperature and location should be clearly marked on the product label or product specification documents. As a guideline recommendation is for T_c marking on the driver housing.

9 EMI - ELECTROMAGNETIC INTERFERENCE

LED drivers operate at high frequency, they may produce Electromagnetic Interference (EMI) or Radio Frequency Interference (RFI). RFI frequencies are a subset of EMI frequencies. EMI issues cover all possible operating frequencies while RFI is only concerned with radio and television frequencies. This interference could affect the operation of sensitive electrical equipment, such as radios, televisions or medical equipment.

9.1 Types

9.1.1 *Conducted Emission*

Interference conducted via mains (terminal interference voltage). Poor filtering / no grounding results higher conducted emission. This pollutes mains supply.

9.1.2 *Radiated Interference*

Interference due to Electro Magnetic radiation. This affects other equipment.

9.2 Applicable Standards

a) CISPR 15 (for frequency range 9KHz to 30 MHz);
b) EN55022A (for frequency range > 30 MHz); and
c) FCC Class A (for frequency range 450 KHz to 30 MHz).

10 EMC - EMISSION AND IMMUNITY REQUIREMENTS

To ensure proper operation and immunity to external electrical disturbances and minimize emissions, the following criteria shall be met.

10.1 Electromagnetic Interference Suppression

Drivers shall comply with government regulations for reference use CISPR15.

10.2 Line Transient (Surges)

Electronic drivers are susceptible to line transients; therefore, transient protection shall be included. The guidelines for this protection shall be as described in IEC 61000.

11 TLA - TEMPORAL LIGHT ARTIFACTS

Change in visual perception, induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a human observer in a specified environment.

11.1 Flicker

Perception of visual unsteadiness induced by a light stimulus the luminance or spectral distributionof which fluctuates with time, for a human observer in a specified environment. *~0-80Hz.*

11.2 Stroboscopic Effects

Change in motion perception induced by a light stimulus the luminance or spectral distribution ofwhich fluctuates with time, for a static observer in a non-static environment. *~80Hz-2kHz.*

11.3 Phantom Array Effects

Change in perceived shape or spatial positions of objects, induced by a light stimulus the luminanceor spectral distribution of which fluctuates with time, for a non-static observer in a staticenvironment.

11.4 Problem with TLA

a) May cause eye strain or headaches, may impair visual or cognitive performance, Distracting;
b) May trigger medical conditions (in severe cases);
c) Interferes with optical equipment (cameras, bar code readers, etc.); and

d) Could slow adoption of LED lighting due to perceived poor performance.

11.5 LEDs flicker

They faithfully reproduce light based on the amount of current flowing through them. Primarilydriver is responsible for that. Right driver design can eliminate these effects.

11.6 Sources of TLA

a) Source voltage changes (noise);
b) Externally coup LED noise sources;
c) Dimmer phase angle instabilities (when dimming);
d) Driver instabilities; and
e) Driver (intended) operation.

11.7 Current TLA/TLM Measures

11.7.1 *Simple*

Percent Flicker and Flicker Index.

11.7.2 *Complex*

PST LM and SVM.

11.8 Flicker Testing (PST)

IS 14700 (Part 4/Sec 15), IS 14700 (Part 3/Sec 3) and IEC TR 61547 may be referred for flicker testing. Below Fig. 24 illustrates block diagram of flicker testing.

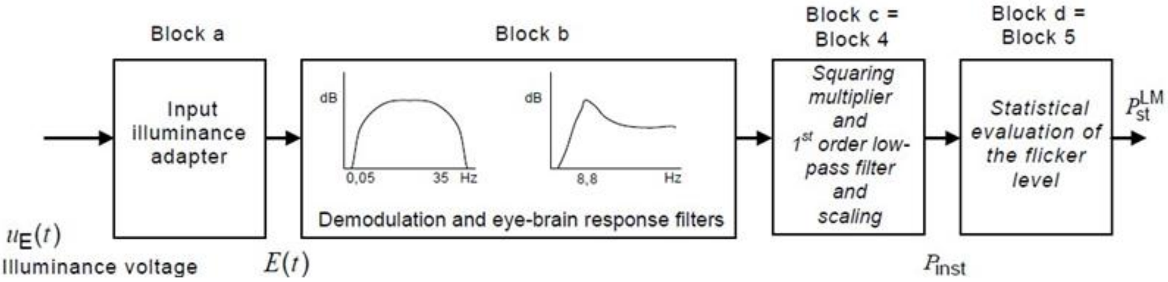


Fig. 24 Flicker Testing

Below Fig. 25 shows graph of modulation depth and frequency

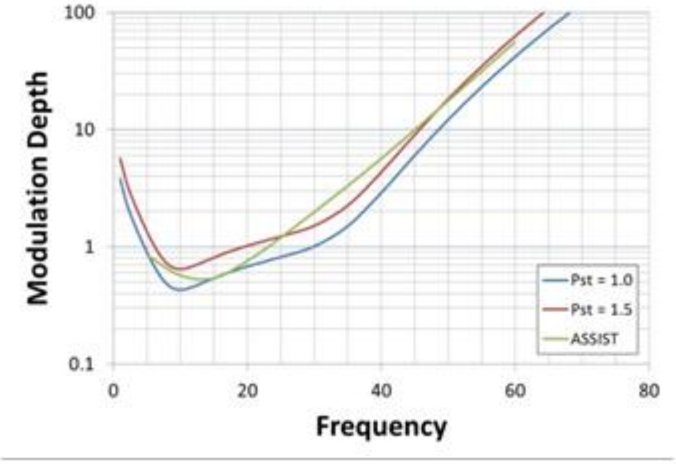


Fig. 25 Graph of Modulation Depth and Frequency

11.9 Stroboscopic Visibility Measure (SVM)

a) Measures stroboscopic effects >50Hz.
b) Intended for indoor office-type environments.

Below Fig. 26 Shows SVM Approach.

SVP Approach

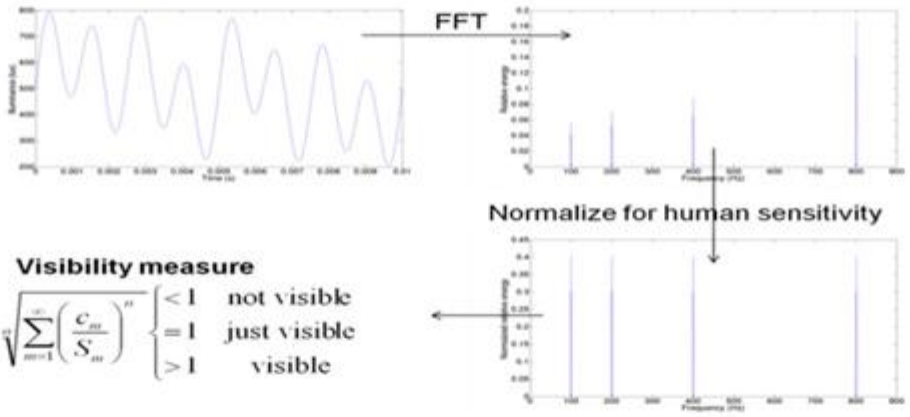


Fig. 26 SVM Approach

Below Fig. 27 shows comparison of different TLA specifications

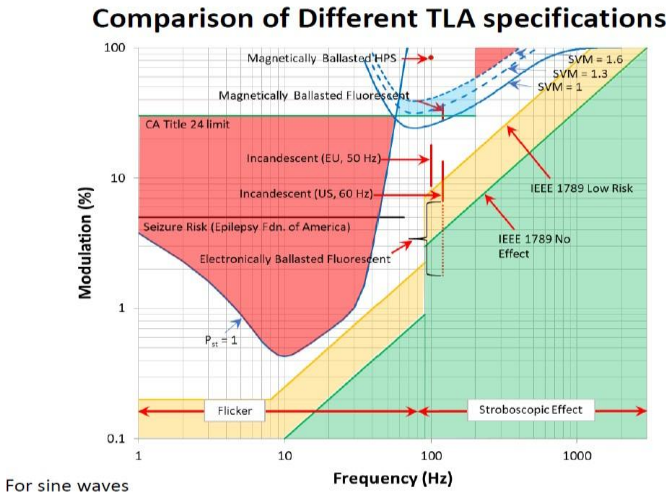
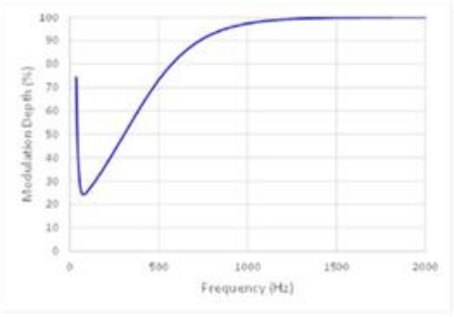


Fig. 27 Comparison of Different TLA Specifications

c) Based on human perception trials; and
d) Accounts for frequency and wave shape.

11.10 Human Eye Sensitivity Stroboscopic Only, Sine Wave

Below Fig. 28 shows plot of visibility threshold.



Plot of the Visibility Threshold

Tm(f) for the stroboscopic effect, expressed in terms of modulation depth, as a function of frequency. The curve is for a single sine wave modulation

Fig. 28 Plot of Visibility Threshold

Below Fig. 29 shows metrics for evaluating flicker.

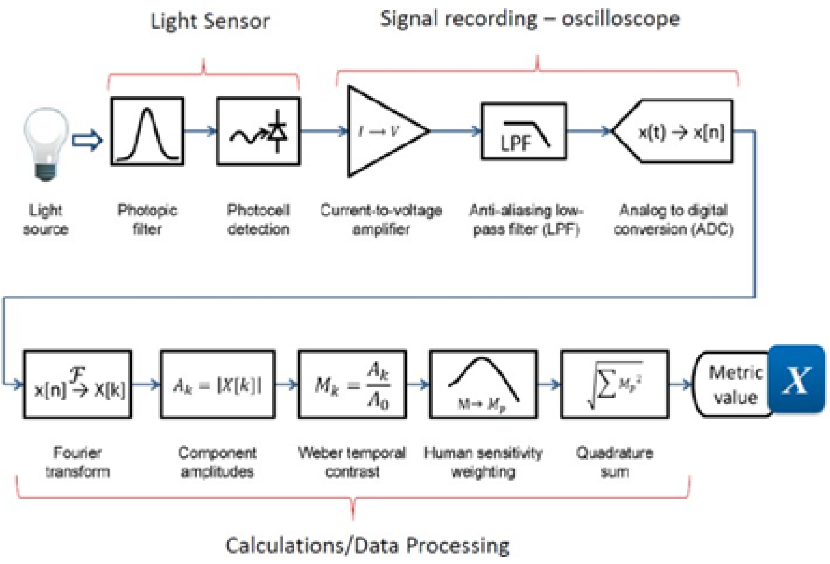


Fig. 29 Metrics for Evaluating Flicker

11.11 Basic SVM Measurement

see Table 2.

Table 2 SVM Measurement

(*Clause* 11.11)

Sl No.	Product Application Area	Pst^{LM} Limit	SVM limit
(1)	(2)	(3)	(4)
i)	Outdoor	≤ 1.0	None
ii)	Indoor	≤ 1.0	≤ 1.6

12 SAFETY REQUIREMENT

Drivers shall comply with IS 15885 or other safety standards as applicable, including but not limited to the following parameters:

a) Normal Temperature Operation Test;
b) Dielectric Withstand Test;
c) Leakage Current Test and Dielectric Voltage Withstand Test After Humidity Exposure;
d) Leakage Current Test;
e) Maximum Output Voltage Test;
f) Strain Relief Test;
g) Endurance Test on Overcurrent / Over temperature Devices;
h) Abnormal Tests (transformer burnout, reverse polarity, component breakdown, overload); and
j) Dry, Damp, Wet Location Test (Humidity, Standing Water Test, Rain Test, etc.)

13 DRIVER PERFORMANCE GUIDELINE

13.1 General

The LED driver shall maintain the specified performance throughout its lifetime under the operating conditions specified. The driver should be tested per the requirements in IS 16104.

> **NOTE —** If a driver can operate over a wider range of voltages or currents than specified, this should be identified by the manufacturer.

13.2 Operating Conditions

For reliable operation, a driver for LEDs shall be designed to meet the operating parameters of Section 3 when tested at a temperature of 25 ±5 °C.

13.3 LED Driver Input

A power line circuit having a maximum impedance as specified by IS 16104 shall be used to determine compliance with this section.

13.3.1 *Operating Supply Voltages*

When operated at any supply voltage between 90 percent and 110 percent of its rated supply voltage and at rated input frequency, a driver shall provide current and/or voltage regulation that equals or exceeds the values specified by the manufacturer.

13.3.2 *Input Current Harmonic Distortion*

The harmonic distribution of the input current shall comply with the requirements of IS 14700 (Part 3/Sec 2).

13.3.3 *Input Inrush Current*

There is a need to control inrush current transients caused by capacitor charging. Inrush currents shall be limited as specified in the manufactures data sheet.

13.3.4 *Input Current*

The LED driver input current, expressed in amps, shall be measured at the nominal input voltage of 230 or 440 V a.c. be connected to a branch circuit as described above in **3.2**, and have connected to the output the maximum load whether it be a LED array, module(s), or package(s).The LED driver input current for a dynamic range LED driver should be measured at the minimum nominal driver input voltage and at the maximum nominal driver input voltage.

13.3.5 *Input Power*

The LED driver wattage, expressed in watts (W), shall be measured at the nominal driver input voltage and have connected to the output of the maximum load whether it is LED array(s), module(s),or package(s). The LED driver input power for a dynamic range LED driver should be measured at the minimum nominal driver input voltage and at the maximum nominal driver input voltage.

13.3.6 *Power Factor*

The LED driver power factor, expressed as a decimal never greater than 1, shall be measured at the nominal driver input voltage and have connected to the output the maximum load whether it be LED array(s), module(s), or package(s). The LED driver input power factor for a dynamic range LED driver should be measured at the minimum nominal driver input voltage and at the maximum nominal driver input voltage.

13.4 Driver Output

13.4.1 *Constant Voltage Regulated Output*

When operated at its rated supply voltage and frequency, a driver shall deliver a voltage within ±10 percent of its nominal output voltage over the entire voltage control LED operating load range.

13.4.1.1 *Load regulation*

When operated at its rated supply voltage and frequency, a driver shall deliver a voltage within ±5 percent, or the value specified by the manufacturer, of its nominal output voltage over the entire operating load range.

13.4.1.2 *Line regulation*

When operated at its rated supply frequency and with any supply voltage within ±5 percent of the rated supply voltage, the driver shall deliver a voltage within ±5 percent, or the value specified by the manufacturer, of its nominal output voltage over its operating load range.

13.4.1.3 *Output voltage ripple*

For d.c. output drivers, the total voltage ripple due to reflected mains frequency and high frequency shall be limited to ±10 percent, or the value specified by the manufacturer, of the nominal output voltage.

NOTE — Low frequency ripple should be minimized to reduce LED flicker.

13.4.2 *Constant Current Regulated Output*

When operated at its rated supply current and frequency, a driver shall deliver a current within ±10 percent, or the specified value by the manufacturer, of its nominal output current over the entire current control LED operating load range.

13.4.2.1 *Load regulation*

When operated at its rated supply voltage and frequency, a driver shall deliver a current within ±10 percent, or the specified value by the manufacturer, of its nominal output current over the operating load range.

13.4.2.2 *Output current ripple*

Total current ripple should be minimized to reduce LED flicker.

13.5 Dimming Regulated Output

13.5.1 *Load Regulation*

When operated at its rated supply voltage and frequency, a driver shall deliver a voltage or current within ± 10 percent, or the specified value by the manufacturer, of its nominal output voltage or current over the entire operating load range.

13.5.2 *Line Regulation*

When operated at its rated supply frequency and with any supply voltage within ±10 percent of the rated supply voltage, a driver shall deliver a voltage or current within ±10 percent, or the specified value by the manufacturer, of its nominal output voltage or current over the operating LED load range.

14 LED DRIVER CHECK LIST CONSTRUCTED ON KEY CHARACTERISTICS

14.1 Accuracy

Accuracy is the closeness of the measurement to specific value. In terms of LED drivers, it is defined in percentage and the range is typically between +/- 2 percent to +/- 5 percent. For an example the LED driver with Output of 700 mA, 50V having an accuracy of +/- 5 percent should not deviate beyond the window of +5 percent and -5 percent. For example 735 mA-665 mA, 52.5V-47.5V. 5 percent accuracy is considered good enough in LED driver circuits. Higher accuracy results in more précised output.

14.2 Lifetime

An LED driver converts a.c. to d.c. efficiently, but any energy lost in the process becomes heat, causing thermal stress on the circuit. For example, a 90 percent efficient driver powering a 100 W load requires 111W input, with 11W lost as heat.

When housed with LEDs, additional heat raises the driver’s temperature, affecting reliability, especially for electrolytic capacitors, which degrade faster at high temperatures. Reducing the operating temperature by 10 °C can double the lifespan, per Arrhenius Law. To ensure longevity, drivers must operate below their TC point or use long-life components.

Below Fig. 30 shows capacitor life graph.

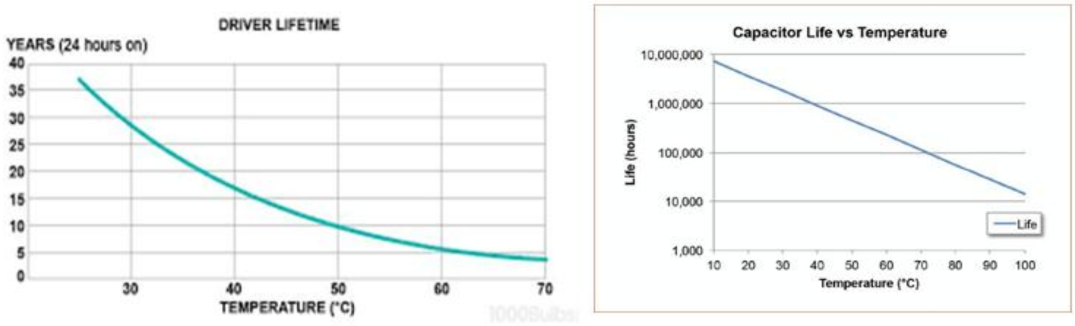


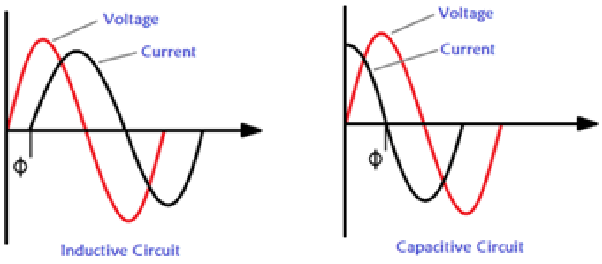
Fig. 30 Capacitor Life Graph

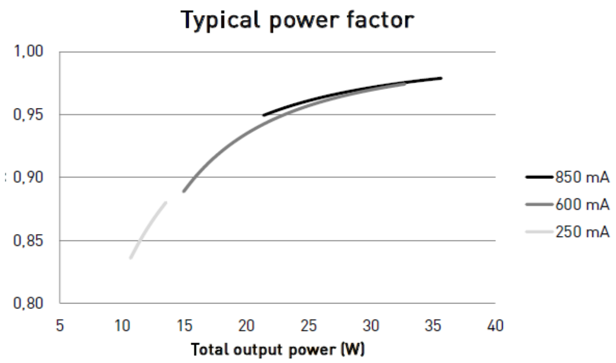
To facilitate heat dissipation, LED drivers for high wattage LED luminaires use aluminium enclosures which can come with high density fins and thermally conductive potting.

14.3 Power Factor

Power factor (PF) (*see* Fig. 31) is the ratio of power used to power delivered, ranging from 0 to 1. A resistive load has a PF of 1, but reactive components like capacitors and inductors in LED drivers draw additional reactive power, increasing apparent power and straining utility infrastructure.

A lower PF wastes power as reactive energy, and utilities may impose surcharges for low-PF equipment in commercial and industrial settings. Power factor correction (PFC) circuits, using active or passive methods, minimize reactive power by aligning the input current with the line voltage.





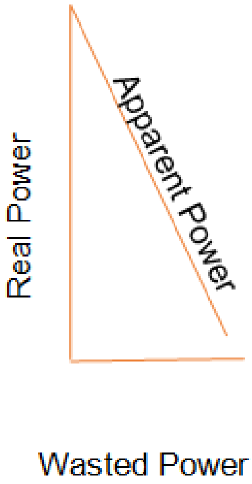


Fig. 31 Power Factor

14.4 THD - Total Harmonic Distortion

Total Harmonic Distortion (THD) measures waveform distortion caused by non-linear loads, such as rectifiers. High THD reduces power factor (PF), distorts current waveforms, and can damage power distribution systems.

THD is expressed as a percentage, with lower values being better. Regulatory limits (typically <20 percent) ensure LED drivers minimize harmonic distortion across the input voltage range. PFC circuits help suppress THD by shaping the input current.

PF and THD can be impacted by dimming, so both must be measured at full and dimmed outputs.

Below Fig. 32 shows voltage and current waveforms for a linear power supply and Fig.33 shows harmonics of current flowing into a linear power supply.

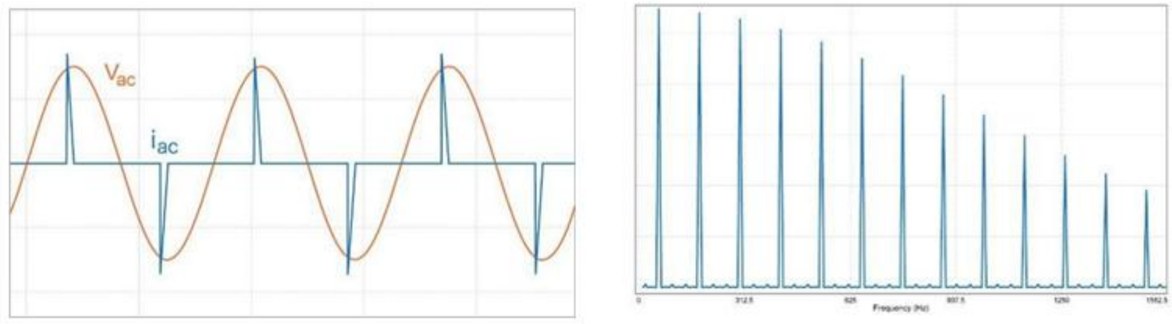


Fig. 32 Voltage and Current Waveforms for a Linear Power Supply

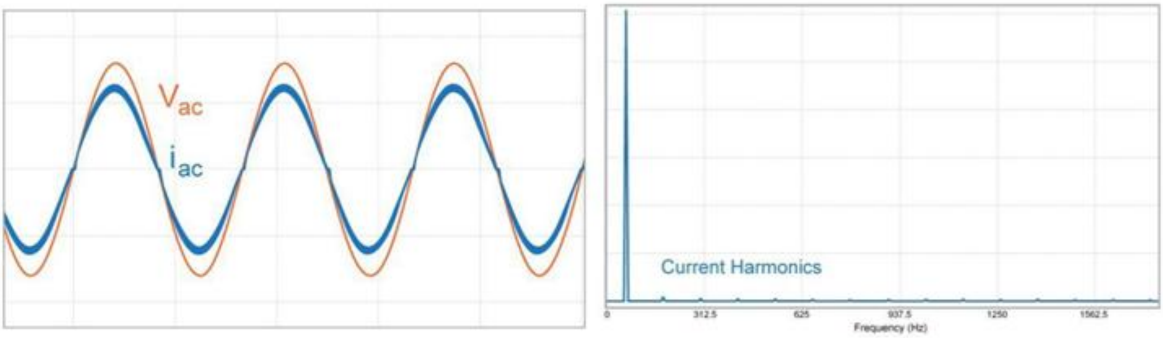


Fig. 33 Harmonics of Current Flowing into a Linear Power Supply

14.5 Efficiency

Efficiency, expressed as a percentage, is the ratio of output power to input power, typically specified at full load and nominal voltage. For example, a 50 percent efficient power supply delivering 50W draws 100W, wasting 50W as heat. A 90 percent efficient supply draws only 56W for the same load, reducing losses and energy consumption.

Efficiency varies with environmental and load conditions, peaking at 50 percent load, where manufacturers guarantee maximum performance. While higher wattage supplies may cost more, they offer benefits like lower electricity bills, reduced heat, and quieter operation. Supplies are generally more efficient at 230V than at 110V. Below Fig. 34 shows efficiency curve.

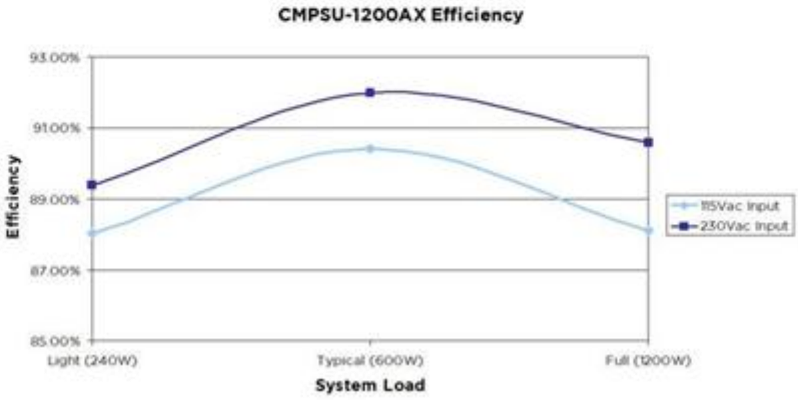


Fig. 34 Efficiency Curve

14.5.1 *Losses in Power Supply Efficiency*

It is not possible to achieve 100 percent power supply efficiency due to energy losses, but with proper design and component selection, high efficiencies of between 95 percent and 97 percent are possible. Losses in power supplies occur due to passive and active components power losses. In SMPS, losses occur in the switching devices such as MOSFETS, and other junction-based semiconductors such as the diodes. Other losses occur in the capacitors and inductors especially when cheap, high resistance components are used.

14.5.2 *Passive Component Losses*

a) Resistor losses;
b) Inductor losses due to Core and winding losses of inductors; and
c) Capacitor losses.

14.5.3 *Active Component Losses*

MOSFET and diodes conduction and switching losses.

The MOSFETS and diodes are responsible for most of the power losses due to conduction and switching losses. The conduction losses occur due to the on-resistance of the MOSFET, and the forward voltage of the diode. Diodes have larger conduction losses which are proportional to the forward currents.

14.6 Ripple Factor

Flicker is the modulation of light output caused by a.c. voltage fluctuations, current ripples, or dimming circuit interactions. It can lead to temporal light artifacts (TLAs), including visible flicker (≤80 Hz), invisible flicker (≥100 Hz), stroboscopic effects, and phantom arrays. TLAs may cause eye strain, visual discomfort, migraines, or even photosensitive seizures, making flicker a critical consideration for indoor lighting and visual tasks.

Flicker-free lighting is essential for homes, offices, and studios, where precision and prolonged exposure matter. LED drivers play a key role in mitigating flicker by filtering current ripples, typically ≤2 percent for applications requiring high light quality. However, a.c. LED systems are prone to flicker due to rapid polarity changes.

IES metrics like percent flicker and flicker index quantify flicker, with 10 percent flicker at 120 Hz considered tolerable for most people, while 4 percent or less is safe for all. Despite the need for low flicker, many LED products on the market still exceed 30 percent flicker at 120 Hz. Below Fig. 35 shows ripple.

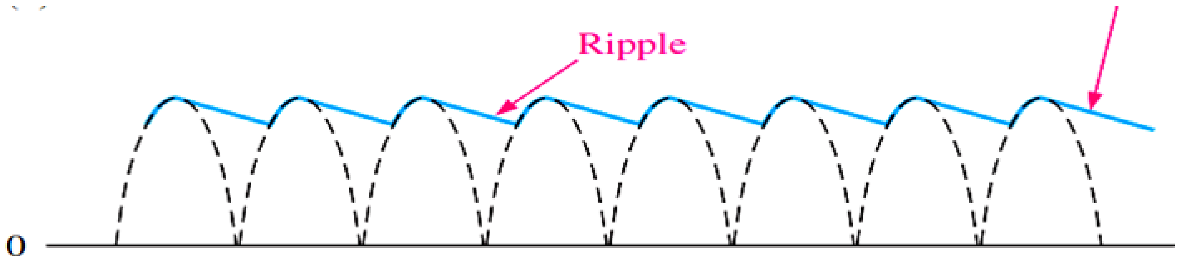


Fig. 35 Ripple

14.7 Surge Protection

LED drivers face challenges like overcurrent, overvoltage, undervoltage, short circuits, open circuits, improper polarity, loss of neutral, and overheating, depending on topology, design, and environment. Protection mechanisms are essential to address these issues.

Open circuit protection prevents excessive output voltage in constant current drivers, using Zener diodes or active feedback to shut down the supply. Input overvoltage protection (IOVP) safeguards drivers from grid surges, lightning, and electrostatic discharge using MOVs, TVS, or capacitors. For applications like street lighting, surge protection devices (SPDs) rated for 10 kV/10 kA (ANSI C136.2) are recommended.

Short circuit protection varies by driver type. Linear supplies limit current to prevent overheating, while switching regulators risk module failure. Self-adjusting circuits can balance voltage changes, and duty cycle monitoring detects faults in LED strings.

Over-temperature protection includes Module Temperature Protection (MTP) and Driver Temperature Limit (DTL). These use NTC resistors or sensors to reduce current when module or driver temperatures exceed safe limits, ensuring system reliability.

14.8 EMI and EMC

Electromagnetic interference (EMI), or radio frequency interference (RFI), arises from electromagnetic conduction or radiation emitted by devices like LED drivers. LED drivers connected to a.c. mains must comply with EMI standards such as IEC 61000-6-3.

MOSFET switching in LED circuits is a primary EMI source. To minimize EMI, PCB layouts should have short, compact switching paths, and input filters may be used to reduce high-frequency harmonics. A continuous ground plane prevents current loops, and metal enclosures can block EMI radiation.

14.9 Safety Considerations

Safety is paramount when evaluating LED drivers and lighting systems. Line-powered drivers with dielectric isolation (For example 1500 V RMS) between input and output are ideal, achieved using transformers with good galvanic isolation. Output voltage must stay below the 60 VDC SELV limit (IEC 61140). However, non-isolated designs are increasingly common to reduce costs, posing electric shock risks due to inadequate isolation or insulation.

Creepage and clearance distances must meet requirements to avoid electrocution, fire, or arcing. Proper PCB design is critical to address these issues while minimizing EMI.

Protection Class I drivers must have all conductive parts connected to earth, while Class II drivers rely on reinforced insulation to separate mains power from output circuits, ensuring safety without grounding the enclosure.

14.10 Thermal Consideration

An LED driver converts a.c. voltage to d.c. efficiently, with any energy loss converted to heat. For example, a 90 percent efficient driver requires 111W input to deliver 100W output, with 11W lost as heat. This heat places thermal stress on the driver, especially when housed with the LEDs, further increasing its temperature.

To ensure reliability, drivers must use high-temperature-rated components and dissipate heat effectively, as excess heat can damage sensitive parts like electrolytic capacitors. High-wattage

LED drivers often use aluminum enclosures with fins and thermally conductive potting to enhance heat dissipation and prolong lifespan.

14.11 Ingress Protection

LED drivers for outdoor and industrial applications must be sealed to prevent dust, moisture, and water ingress. High ingress protection (IP) ratings are essential for environments like carwashes, cleanrooms, food processing facilities, and other industries requiring frequent high-pressure wash downs. Drivers for wet locations are often potted in silicone to ensure enclosure integrity, electrical insulation, and effective thermal management. Common IP ratings for such drivers include IP65, IP66, and IP67.

14.12 Location Impact

LED drivers can be remote mounted or co-located within lamp or luminaire housings. In co-located, non-DOB systems, the driver must be thermally isolated from LEDs which generate a huge amount of heat. Driver maintenance should be taken into consideration when designing a luminaire housing.

In remote-mounted systems, PWM drivers can experience performance losses over a long distance. As such, CCR (Constant current reduction) is the preferred dimming technique for remote- mounted systems.

ANNEX A

(*Clause* 2)

LIST OF REFERRED STANDARDS

IS No.	*Title*
IS 14700 (Part 3/Sec 3): 2018	Electromagnetic compatibility (EMC): Part 3 limits Section3 limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply system, for equipmentwith rated current 16 a per phase and not subjected to conditional connection (Second Revision)
IS 14700 (Part 4/Sec 15): 2018	Electromagnetic compatibility (EMC): Part 4 testing and measurement techniques: Sec 15 flickermeter - Functional and design specifications (Second Revision)
IS 14700 (Part 3/Sec 2): 2020	Electromagnetic Compatibility (EMC) Part 3 Limits Section 2 Limits for harmonic current emissions (equipment input current 16 A per phase) (Third Revision)
IS 14700 (Part 4/Sec 5): 2019	Electromagnetic compatibility (EMC): Part 4 testing and measurement techniques Section 5 surge immunity test (First Revision)
IS 15885 (Series)	Safety of lamp controlgear
IS 16101:2012	General lighting - LEDs and LED modules —Terms anddefinitions
IS 16102 series	Self- ballasted LED lamps for general lighting services
IS 16104 : 2012	D.C. Or A.C. Supplied Electronic Control Gear for LED Modules — Performance Requirements
CISPR 15:2018	Limits and methods of measurement of radio disturbancecharacteristics of electrical lighting and similar equipment
IEC TR 61547-1:2020	Equipment for general lighting purposes - EMC immunity requirements - Part 1Objective light flickermeter andvoltage fluctuation immunity test method
IEC 60068-2-6:2007	Environmental testing - Part 2-6: Tests - Test Fc: Vibration (sinusoidal)
IEC 61000-6-3: 2020	Electromagnetic Compatibility (EMC) - Part 6-3: Generic Standards - Emission Standard for Equipment in Residential Environments
IEC 61140:2016	Protection Against Electric Shock - Common Aspects for Installation and Equipment
IEC 62386-101:2022	Digital Addressable Lighting Interface - Part 101: General Requirements - System Components
EN 55022: 2010	Information Technology Equipment – Radio disturbancecharacteristics – Limits and methods of measurement
ANSI C82.16 :2022	Light-Emitting Diode Drivers