SCL
Lichtlösungs GmbH

CORRECT DIMMING OF LED LIGHTING

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A guide to dimming your LED lighting

The ability to adjust the brightness of the lighting offers numerous benefits, from creating the perfect ambience for different activities to saving energy and extending the service life of light sources. There are a variety of dimming technologies for LED lighting, each with its own characteristics, advantages and considerations. This guide provides a comprehensive overview of these different dimming methods to help you select the most suitable solutions for your customers' needs.

1. Understanding LED dimming

Dimming LED luminaires offers a variety of benefits that improve both the functionality and attractiveness of LED lighting systems. One of the main advantages is the ability to create different atmospheres and moods in one room. By adjusting the light intensity, users can move from bright, focused lighting suitable for tasks to softer, more relaxed lighting for leisure activities. This flexibility allows the lighting to adapt to different needs throughout the day and improve the usability of any environment.

In addition to the ambience, dimming LEDs also makes a significant contribution to saving energy. The reduction in brightness leads directly to lower electricity consumption, which results in lower electricity bills and a smaller ecological footprint. In addition, operating LEDs at lower intensity generates less heat, which in turn reduces the load on the components and can significantly extend the service life of the LED lights. Additionally, the ability to finely adjust light intensity can contribute to improved light quality and reduced eye strain, creating a more comfortable and productive environment.

To achieve these benefits, various dimming methods have been developed for LED lighting. This guide examines 14 different techniques, including leading edge/trailing edge, push button closure, DALI, DALI or push, 1-10V, 1-10V and push, PWM, PWM and push, RF radio, RF radio and push, KNX, leading edge phase, trailing edge phase, step dimming and voltage sink. Each of these methods uses a specific approach to regulating the light output of LEDs, often involving certain types of dimmers, drivers and control signals. The optimal choice of dimming method depends on a variety of factors, such as the type of LED light source used, the desired level of control and sophistication, the specific application environment and the overall budget for the lighting system. Understanding the nuances of each dimming technology will enable your customers to make informed decisions and achieve the best possible lighting results.

2. Detailed explanation of LED dimming technologies

2.1. leading edge/trailing edge dimmer (leading edge/trailing edge)

Leading edge/trailing edge dimmer is a widely used technology for controlling the brightness of light sources by interrupting the AC waveform that supplies power to the luminaire. This interruption is achieved by an electronic switch, typically a triac, which selectively allows current flow for only a portion of each AC cycle. There are two main types of leading edge phase/trailing edge dimming: leading edge phase and trailing edge phase edge.

Leading edge phase (leading edge dimming)
Phase-angle dimming works by delaying the point in time in each AC half-wave at which the current flow begins. By shifting the start of the current flow, the average power supplied to the LED is reduced, resulting in a reduction in brightness. Historically, this method was mainly used for resistive loads such as incandescent and high-voltage halogen lamps. Although some dimmable LEDs are compatible with leading edge phase control dimmers, it is crucial to check this compatibility with the LED manufacturer as this type of dimmer may not always work optimally with the electronic circuitry of many LED productsoptimally.

Trailing edge phase (trailing edge dimming)
In contrast to leading edge dimming, trailing edge dimming allows the current to flow at the beginning of each alternating current half-wave, but interrupts the flow before the end of the period. By switching off the current towards the end of the period, the average power supplied to the LED is reduced, thus dimming the light. Trailing edge dimmers, which often use MOSFET transistors, are generally considered the better choice for dimming LED loads. They tend to offer smoother dimming performance and are less likely to cause problems such as flickering or humming compared to leading edge phase control dimmers when used with LEDs.
Modern dimmable LED drivers often have sophisticated electronics that can interpret the incoming leading edge phase or trailing-edge signal and convert it into a precise control current suitable for the LED. This ensures that the LED is dimmed correctly and efficiently.

Advantages
Leading edge phase/trailing edge dimming is relatively easy to install and often allows for direct replacement of existing light switches, which is particularly practical for converting existing installations to LED. It also utilizes existing electrical wiring within a building, minimizing the need for new cabling. Compared to more advanced dimming systems, leading edge phase/ trailing edge dimmer generally have lower initial costs, making them an attractive option for budget-conscious projects. In addition, a wide range of leading edge/trailing edge dimmers and LED products claiming compatibility are readily available.

Disadvantages
The dimming range achievable with leading edge phase/trailing edge dimming for LEDs can sometimes be limited , with some LEDs not being able to be dimmed to very low brightness levels. Flickering or humming noises may occur, especially at lower dimming levels or if an incompatibility exists between the dimmer and the LED used. Leading edge phase/ trailing edge dimmer can also generate electromagnetic interference (EMI), which can affect other sensitive electronic devices. In terms of energy efficiency, leading edge phase/trailing edge dimming may be less efficient compared to some other methods such as pulse width modulation (PWM). Finally, ensuring compatibility between the dimmer and the LED load can sometimes be difficult due to the lack of universal standards for electronic loads, and many older dimmers have minimum load requirements that may not be met by energy efficient LEDs.

Areas of application
Leading edge phase/trailing edge dimming is often used in residential areas, especially when converting from conventional incandescent or halogen lighting to LED. It is also suitable for applications where a basic level of dimming control is desired and cost is an important factor. With careful selection of compatible components, leading edge phase/trailing edge dimming can also be used in certain commercial installations.

Required components
The essential components for leading edge phase/trailing-edge dimming are a leading edge phase-/ trailing edge dimmer, which can be either leading-edge (RL) or trailing-edge (RC) type, although trailing-edge or universal dimmers (RLC) are generally recommended for LED compatibility. It is also necessary to have dimmable LED light sources (lamps or luminaires) that are explicitly labeled as compatible with leading edge/trailing edge dimmer. A compatible LED driver is often required, which can be integrated into the LED lamp or provided as a separate unit.

2.2. Push button dimming (push button closure)

Push-button dimming, also known as „push-to-make" dimming, offers a simple and intuitive way to control LED lighting with a momentary push button. This method is based on short and long button presses to perform different functions.

How it works
A short press of the push button typically turns the LED lights on or off. A longer press, which is usually held for one second or longer, starts the dimming process. The brightness of the lights then changes cyclically upwards or downwards as long as the push button is pressed. Releasing the push button at the desired brightness level sets the light to this intensity. Some systems can change the dimming direction (up or down) with each subsequent long press. Many push-dim systems also have a memory function that enables the lights to return to the last set brightness level when they are switched back on after being switched off.

Advantages
Push button dimming is characterized by its simple operation, making it easy for users to understand and use. A single push button can often be used to control multiple LED lights connected to compatible drivers or controllers, creating a central point of control. This method is particularly easy to integrate into existing electrical installations, especially in renovation projects, as it often only requires a simple two-wire connection between the push button and the LED driver or controller. In addition, the push button dimming function is often integrated into more advanced dimming systems such as DALI and 1-10V, offering a versatile range of control options.

Disadvantages
The specific wiring requirements for push button dimming may vary depending on the LED driver or controller used, so it is important to consult the product documentation. The degree of precision and dimming speed may not be as finely adjustable as with rotary or slide dimmers. In simpler multi-channel systems, the independent control of different lighting zones may be limited if push button dimming is used exclusively.

Areas of application
Push button dimming is a versatile solution that is suitable for both residential and commercial environments where a user-friendly and uncomplicated dimming method is desired. It is often used in offices, educational institutions, retail spaces and the hospitality industry. Its ease of installation makes it particularly attractive for renovation projects where laying new control lines could be difficult.

Components required
The core components for push button dimming are a momentary push button (closing switch), which should be of the „normally open" type and returns to its original position when released, and an LED driver or controller that has a dedicated „Push Dim" input. The LED light sources (lamps or LED strips) must be compatible with the selected driver or controller.

2.3. DALI (Digital Addressable Lighting Interface)

DALI, the abbreviation for Digital Addressable Lighting Interface, is a sophisticated and standardized digital communication protocol specifically designed for controlling lighting systems. It enables precise and individual control of each luminaire or group of luminaires within a lighting system.

How it works
DALI works via a dedicated two-wire bus that transmits digital control signals between a DALI controller (often referred to as the master) and DALI-compatible LED drivers or other lighting control devices (slaves). This bus not only transmits control information, but also supplies the connected DALI devices with power. An important feature of the DALI bus is that the wiring is insensitive to polarity, which simplifies the installation process. The DALI protocol supports bidirectional communication so that the control system can receive feedback from the luminaires, e.g. their current brightness level or operating status. Each DALI device on the bus can be addressed individually, which enables granular control. The system also supports the grouping of luminaires into zones, allowing several luminaires to be controlled simultaneously. A single DALI line can typically address up to 64 individual devices.

Advantages
DALI offers very precise and flexible control of light levels, enabling fine-tuning of brightness and the creation of complex lighting scenes. The system is highly scalable and is therefore suitable for large and complex lighting installations in commercial buildings and other large spaces. DALI supports advanced lighting management functions, including the ability to recall preset lighting scenes, schedule lighting changes based on time or presence, and integrate with building management systems to improve energy efficiency and automated control. In addition, DALI offers consistent dimming performance across all connected luminaires, ensuring uniformity of the lighting effect.

Disadvantages
The initial cost of implementing a DALI system can be higher than with simpler dimming methods due to the need for special DALI-compatible LED drivers and a DALI master controller. Installation can be more complex and require adherence to specific DALI wiring guidelines, often including programming and commissioning the system to assign addresses and configure control parameters.

Areas of application
DALI is mainly used in commercial buildings, offices, retail spaces, architectural lighting and other applications where sophisticated and flexible lighting control is essential. It is also ideal for projects where energy efficiency, central control and integration with other building systems are important design considerations.

Required components
To implement a DALI dimming system, a DALI master controller is required to initiate and manage communication on the DALI bus. DALI-compatible LED drivers are required to receive and interpret the DALI control signals and adapt the light output accordingly. A dedicated two-wire DALI bus is required to connect the controller and the drivers. In many cases, a separate DALI power supply is required to power the bus, although some master controllers may have an integrated power supply.

2.4. DALI or Push

Many LED driver manufacturers recognize the need for flexibility in lighting control and now offer devices that support dual control interfaces so that they can be operated either via the digital DALI protocol or via a conventional push button.

How it works
These "DALI or Push" drivers can be integrated into a complete DALI system and receive and respond to digital commands from a DALI master controller. Alternatively, they can be controlled locally via a standard momentary push button connected to a dedicated input on the driver. When controlled via the push button, the driver typically offers simple on/off switching with a short press and dimming functions (usually an up/down cycle) with a long press.

Advantages
This dual control capability provides a versatile lighting solution that can adapt to different control needs within a project. It can provide a migration path that makes it possible to start a lighting installation with simple push-button control and upgrade it to a more sophisticated DALI system in the future without replacing the LED drivers. It can also provide a degree of redundancy and ensure that the lighting can still be controlled if one of the control methods has a problem. For retrofit projects, using the existing wiring for push-button control can be an easier first step than installing a full DALI bus.

Disadvantages
The push dim functionality offered by these dual interface drivers may be more limited in terms of advanced features and customization options compared to a dedicated DALI system. It is important to use LED drivers that specifically support both DALI and push dim control inputs in order to utilize this functionality.

Areas of application
„DALI or Push" drivers are well suited to projects where simple manual dimming is initially desired, with the possibility of future integration into a more comprehensive DALI-controlled system. They are also useful in applications where both simplicity and the option for more advanced digital control are valued.

Required components
The key components for this type of control are an LED driver that supports both DALI and push-dim inputs. If DALI control is to be used, a DALI master controller is also required. A momentary push button is required for push-dim control. The LED light sources must be compatible with the chosen driver.

2.5. 1-10V dimming

1-10V dimming is an established analog control standard used to adjust the brightness of LED lights using a low-voltage direct current (DC) signal in the sector from 1 volt to 10 volts.

How it works
In a 1-10V dimming system, a control voltage of 10V typically corresponds to operating the LED light at 100% of its maximum brightness, while a control voltage of 1V (or sometimes 0V in certain implementations) dims the light to its minimum level, which is often around 10% of the maximum light output. Some 1-10V dimming systems may require a separate switch to turn the LED light off

completely. This dimming method requires a dedicated low-voltage control circuit in addition to the standard power supply cabling for the LED luminaire.

Advantages
1-10V dimming is generally regarded as a simple and reliable method of controlling LED brightness. It enjoys widespread support among LED driver manufacturers, making it a common choice for commercial and industrial lighting applications. The system enables smooth and stepless dimming of the light output over the entire control voltage sector.

Disadvantages
Implementing 1-10V dimming requires additional low-voltage wiring for the control signal, which can make installation more complex compared to some other methods such as leading edge phase/trailing-edge dimming. The dimming range achieved with the 1-10V control may not always be sufficient for 0% light output; often the minimum brightness level is around 10%. Compared to digital protocols such as DALI, 1-10V dimming offers less advanced functions and less granular control of individual luminaires.

Areas of application
1-10V dimming is commonly used in commercial and industrial lighting installations, including offices, educational institutions, retail spaces, and warehouses. It is ideal for applications where smooth, stepless dimming of groups of luminaires is required.

Required components
The necessary components for a 1-10V dimming system are a 1-10V dimmer switch or controller that generates the low-voltage DC control signal. LED drivers equipped with a 1-10V dimming input are also required; these drivers interpret the control voltage and adjust the power output to the LED luminaire accordingly. A low-voltage control cable, typically consisting of two wires (often purple and gray), is required to connect the dimmer/controller to the driver. Finally, the LED lights must be compatible with the 1-10V dimmable drivers.

2.6. 1-10V and Push

To offer improved flexibility in lighting control, some LED driver and controller units are designed to support both analog 1-10V dimming and push button dimming functions.

How it works
These combination devices enable dimming control via a 1-10V signal, which can be provided by a dedicated 1-10V dimmer or an external lighting control system. They also have a push button input that enables local on/off switching and dimming control via a standard momentary-action switch. The push-button control typically works with short presses to switch on/off and long presses to adjust the brightness up or down.

Advantages
This integrated approach provides a versatile lighting control solution that offers both the precision of analog 1-10V control and the convenience of a local push-button interface. This can be particularly beneficial in commercial spaces where a centralized 1-10V control system is used for general lighting management, but individual users also want a simple, local way to adjust the lighting in their immediate sector via a push button. This combination also offers a certain degree of redundancy, so that lighting adjustments are possible even if one of the control methods is temporarily unavailable.

Disadvantages
Using this dual functionality requires LED drivers or controllers specifically designed to support both 1-10V and push-dim inputs. The wiring for such systems can be somewhat more complex than for stand-alone 1-10V or push dim installations, as connections have to be made for both control signals.

Areas of application
This combined control method is well suited to commercial and public spaces where a balance between centralized control and local user interaction is desired. It is also applicable in environments where users may prefer the tactile feedback of a physical push button for basic control, while benefiting from the more precise dimming functions offered by a 1-10V system.

Required components
The necessary components include an LED driver or controller with both 1-10V control inputs and a push-dim input, a 1-10V dimmer switch or controller to provide the analog control signal, and a momentary push button for local control. A suitable low-voltage control line for both the 1-10V signal and the push-button connection is also required, along with LED light sources that are compatible with the chosen driver.

2.7. PWM dimming (pulse width modulation)

Pulse width modulation (PWM) is a highly effective and widely used dimming technology for LED lighting that controls the brightness by quickly switching the power supply to the LED on and off at a high frequency.

How it works
The perceived brightness of the LED is determined by the duty cycle of these fast current pulses. The duty cycle indicates the percentage of time the current is „switched on" within each period. A higher duty cycle means that the LED is switched on for a greater part of the period, resulting in a brighter light, while a lower duty cycle results in a dimmer light. The switching frequency is typically very high, often in the kilohertz sector, so that the human eye cannot perceive the individual pulses and the dimming appears smooth and stepless.

Advantages
One of the main advantages of PWM dimming is that it provides excellent color consistency over the entire dimming range. As the LED is always operated at its full current when it is „switched on", the color output remains constant regardless of the dimming level. PWM also offers a very precise and wide dimming range, which often allows LEDs to be dimmed down to very low brightness levels without any problems. In addition, PWM dimming is an energy-efficient method because the LED is either fully on or fully off, minimizing energy losses during the dimming process. By reducing the average power delivered to the LED, PWM can also help reduce heat generation, which can lead to a longer LED service life.

Disadvantages
PWM dimming can potentially generate electromagnetic interference (EMI) or feedback, especially at higher switching frequencies or with long, parallel LED strips that act as antennas. A PWM frequency that is too low in turn produces stroboscopic effects.

Areas of application
PWM dimming is a particularly popular and effective technique for controlling the brightness of LED flex stripes (LED strips). It is also used in various other LED lighting applications where precise and consistent dimming is required, such as architectural lighting, stage lighting and general lighting. PWM is also crucial for controlling the intensity of individual color channels in RGB and RGBW LED systems in order to achieve a broad color spectrum.

Required components
The key components for PWM dimming are a PWM dimmer or controller, which generates the high-frequency pulses and allows the duty cycle to be adjusted. This is often integrated in LED strip controllers or LED drivers. The LED light sources themselves (LED strips, individual LEDs or LED luminaires) are also essential.

2.8. PWM and Push

The combination of the precise control of PWM dimming with the simplicity of a push-button interface offers a user-friendly and effective lighting control solution.

Mode of operation
In a „PWM and Push" system, a momentary push button is used as the primary control. A short press typically switches the LED lights on or off, while a longer press initiates the dimming process. The underlying dimming mechanism is pulse width modulation, which ensures smooth and consistent changes in brightness. The PWM controller or driver adjusts the duty cycle of the current pulses sent to the LEDs based on user interaction with the push button.

Advantages
This combination provides an intuitive and familiar user experience with the high quality dimming performance of PWM. It is suitable for a wide range of applications where both user-friendliness and precise brightness control are required.

Disadvantages
This method requires an LED controller or driver specifically designed to support both PWM output and a push dim input.

Areas of application
The „PWM and Push" control is often used in residential lighting, including recessed under cabinet lights, workplace lighting and general room lighting. It can also be found in commercial spaces where a simple but effective dimming solution is required.

Required components
The key components for this method are an LED controller or driver with PWM output capabilities and a dedicated push-dim input port, a momentary push button, and LED light sources (LED strips or luminaires) compatible with the PWM controller/driver.

2.9. radio frequency (RF) wireless dimming

Wireless RF (Radio Frequency) radio dimming offers a convenient and flexible way to control LED lighting without additional control cables. This method uses radio waves to send dimming commands from a controller to a receiver connected to the LED lights.

How it works
An RF transmitter, which can be a portable remote control or a wall-mounted wireless switch, sends radio signals to an RF receiver. This receiver is typically connected to the LED driver or integrated into the LED luminaire. The receiver interprets the incoming RF signal and adjusts the brightness of the LEDs accordingly, usually by varying the power supplied to the driver. RF dimming systems often offer functions that go beyond simple dimming, such as on/off switching, scene setting and sometimes color temperature control.

Advantages
The main advantage of wireless RF radio dimming is the elimination of additional control wiring, which greatly simplifies installation, especially for retrofits or where wiring is difficult to access. It offers the convenience of remote control, allowing users to adjust the lighting from a distance. Many RF systems can control several lighting zones or individual luminaires independently of each other, offering a high degree of flexibility in lighting design and management.

Disadvantages
RF signals can be susceptible to interference from other electronic devices operating on similar radio frequencies, which can occasionally affect the reliability of the dimming control. The effective range of the wireless signal may be limited by obstacles such as walls and the power of the transmitter and receiver. Remote controls and some wireless wall switches may require batteries for operation.

Areas of application
Wireless RF radio dimming is suitable for both residential and commercial lighting applications where the convenience of wireless control is desired or where physical wiring is impractical. It is particularly advantageous for retrofitting existing buildings without the need to lay new control cables and for controlling outdoor lighting or luminaires in hard-to-reach places.

Required components
The required components are an RF transmitter (remote control or wall controller) and an RF receiver connected to the LED driver or luminaire. Dimmable LED light sources (lamps or luminaires) that are compatible with the specific RF system are also required.

2.10. RF radio and push

Combining the benefits of wireless RF (Radio Frequency) radio control with a local push-button interface offers users a versatile and convenient way to manage their LED lighting.

How it works
This hybrid approach allows the LED lighting to be controlled via both a wireless RF remote control and a physical push button. The RF remote control offers the convenience of controlling the lights remotely, while the push button provides a familiar and easily accessible local control option. Both methods can typically be used to switch the lights on or off and adjust the dimming level.

Advantages
This combination offers improved flexibility and redundancy in lighting control. Users can choose the control method that best suits their needs at any given time. For example, they might use the remote control for convenience when entering a room, but prefer the tactile feedback of a push button for local adjustments.

Disadvantages
Implementing this dual-control system requires LED drivers or controllers specifically designed to support both wireless RF communication and a push-dim input.

Areas of application
This method is well suited to residential and commercial premises where both the convenience of wireless control and an easily accessible local control option are required. It can be particularly useful in sectors where users frequently want to switch between remote control and a physical switch for instant access to lighting control.

Required components
The necessary components are an RF transmitter (remote control), an RF receiver with a push-dim input connected to the LED driver or luminaire and a momentary push button. Dimmable LED light sources that are compatible with the RF system are also required.

2.11. KNX dimming

KNX is a highly developed and standardized open protocol for building automation that enables the integrated control of various building systems, including lighting. It is a robust solution for comprehensive lighting management in larger projects.

How it works
In a KNX system, lighting control components such as sensors, switches and dimming actuators communicate with LED drivers and luminaires via a dedicated KNX bus. This enables a high degree of centralized and automated control of the entire lighting system. KNX supports a variety of lighting control functions, including on/off switching, dimming, color control for RGB/RGBW LEDs, scene setting and integration with other building systems for energy efficiency and comfort.

Advantages
KNX offers a highly flexible and scalable solution that is suitable for large and complex buildings with extensive automation requirements. It allows for seamless integration of lighting with other building systems such as HVAC, security and shading, resulting in improved energy efficiency and overall building performance. The system offers advanced control functions such as programmable light scenes, time-controlled control, presence-dependent lighting and energy monitoring.

Disadvantages
The initial cost of implementing a KNX system is typically higher than other lighting control methods due to the need for specialized KNX-certified devices and the complexity of the system architecture. Installation and configuration require special knowledge and expertise, often involving certified KNX integrators.

Areas of application
KNX is mainly used in large commercial buildings, smart homes with extensive automation and other projects where the integrated control of multiple building systems is a key requirement. It is ideal for applications where long-term reliability, flexibility and energy management are crucial.

Required components
A KNX system requires a KNX bus power supply, KNX control devices (such as touch panels and sensors), KNX LED dimming actuators connected to LED drivers or lights, KNX-compatible LED drivers or lights and the KNX bus cabling itself.

2.12. Step dimming

Step dimming offers a simple and cost-effective way of achieving a basic dimming function in LED lighting with a standard on/off switch.

How it works
LED lights or drivers with an integrated step dimming function allow users to switch through a limited number of predefined brightness levels (e.g. 100%, 50%, 25%, off) by quickly switching the existing light switch off and on again within a short period of time. Each fast off-on cycle typically switches to the next lower brightness level in the sequence.

Advantages
The main advantage of step dimming is its simplicity, as it does not require the installation of a dedicated dimmer. It uses the existing electrical wiring and standard light switches, which facilitates implementation in new and retrofit installations. This makes it a very cost-effective solution for basic dimming requirements.

Disadvantages
Step dimming offers only a few discrete brightness levels and offers significantly less flexibility and fine-tuning compared to stepless dimming methods. The method of controlling dimming by pressing the light switch may not be immediately intuitive for all users.

Areas of application
Step dimming is suitable for residential and commercial premises where only a few different light levels are occasionally required and the cost of a dedicated dimmer is to be avoided. It can be used in sectors where a simple reduction in brightness is sufficient, such as utility rooms or hallways.

Required components
The main requirement for step dimming is LED light sources (lamps or luminaires) that have an integrated step dimming function in their driver or circuit. A standard on/off switch is used to control the dimming sequence.

2.13. Voltage sink (Voltage Reduction Dimming)

Dimming by voltage reduction involves reducing the voltage supplied to an LED light source in order to reduce its brightness. Although conceptually simple, this is generally not the preferred method for dimming LEDs.

How it works
By reducing the voltage below the nominal operating voltage of the LED, the current flowing through the LED decreases, resulting in lower luminous efficacy. This method was often used with incandescent lamps, where the luminous efficacy is directly proportional to the applied voltage. However, LEDs have a non-linear voltage-current characteristic.

Advantages
The basic concept of voltage reduction for dimming a light is easy to understand.

Disadvantages
Reducing the voltage supplied to an LED can lead to inconsistent and unpredictable dimming behavior. The color temperature of the LED can also shift with the change in voltage. Voltage reduction is generally less energy efficient for dimming LEDs compared to methods such as PWM. The dimming range may be limited and the LED may switch off abruptly below a certain voltage threshold. The use of dimmers designed for incandescent or halogen lamps, which often work by reducing the voltage, can lead to flickering, humming or damage to LED luminaires.

Areas of application
Voltage reduction is generally not recommended for the intended dimming of LEDs. It can occur unintentionally if incompatible dimmers are used.

Required components
This method would typically involve a device that reduces the voltage supplied to the LED, such as a simple resistance or an incompatible dimmer, along with the LED light source itself.

3. Comparative analysis of LED dimming methods

Dimming method	How it works	Advantages	Disadvantages
Phase start/end	Interrupts the AC waveform to reduce the power. Variants for front and rear edge.	Simple installation, uses existing cabling, lower acquisition costs, widely used.	Limited dimming range, potential flicker/hum, EMI, lower efficiency, compatibility issues, minimum load
Push button closure	Short press on/off, long press dims up/down	Simple operation, controls several luminaires, easy retrofitting, can be combined with other protocols.	Wiring may vary, dimming speed/ precision may be limited, limited zone control in simpler systems.
DALI	Digital protocol for individual/ group control via 2-wire bus.	Precise/flexible control, scalable, extended functions (scenes, integration), good dimming range.	Higher purchase costs, complex installation, requires DALI driver/ controller, programming required.
DALI or Push	Accepts control either via DALI bus or push button.	Versatile, migration path, redundancy, easier initial setup.	Push-Dim functionality may be limited, requires drivers that support both methods
1-10V	Analog dimming via 1-10V DC signal.	Simple/reliable, largely supported by drivers, smooth/stepless dimming.	Requires additional low-voltage wiring, dimming range may not reach 0%, less advanced functions than DALI.
1-10V and Push	Combines analog 1-10V dimming with push-button control.	Provides precise analog control and convenient manual operation, useful for central/local control	Requires drivers that support both, cabling may be more complex.
PWM	Switches the power supply on/off quickly, brightness is controlled via the duty cycle.	Consistent color, precise/wide dimming range, energy efficient, reduces heat.	Potential interference, range limitations, battery-operated remote controls/switches.
PWM and Push	PWM dimming, controlled by a push button.	User-friendly interface with high-quality PWM dimming.	Requires drivers/controllers that support both RF and Push-Dim
RF Funk	Wireless control via radio waves from remote control/switch to receiver.	Eliminates control lines, easy installation (retrofit), remote control convenience, controls multiple zones.	Potential interference, range limitations, battery-operated remote controls/switches.
RF Funk and Push	Combines wireless RF radio control with a local push button.	Improved flexibility/redundancy in control options, familiar local control.	Requires drivers/controllers that support both RF and Push-Dim
KNX	Standardized building automation system via a bus network.	Highly flexible/scalable, integrates into other building systems, extended control functions	High acquisition costs, complex installation, requires special knowledge/components
Step dimming	Switches through discrete brightness levels with a standard on/off switch.	Simple implementation, cost-effective, uses existing cabling/ switches.	Limited to a few discrete levels, control method may not be intuitive.
Voltage sink	Dims by reducing the voltage supplied to the LED.	Simple concept.	Inconsistent dimming, potential color change, less efficient, limited sector, may cause flickering/damage

Typical applications	Required components
Residential retrofits, basic dimming needs, some commercial applications.	Leading edge phase/ trailing edge dimmer (RL/RC/RLC), dimmable LED light source, possibly compatible LED driver.
Residential, commercial, office, education, retail, hospitality, renovations.	Momentary push button, LED driver/controller with push-dim input, compatible LED light sources
Commercial buildings, offices, retail, architectural lighting, projects that require sophisticated control.	DALI master controller, DALI-compatible LED driver, 2-wire DALI bus, optional DALI power supply.
Projects with potential for future DALI integration, applications that value simplicity and advanced control.	LED driver with DALI and push dim inputs, DALI master controller (if used), momentary push button (if used), compatible LED light sources
Commercial/industrial, offices, education, retail.	1-10V dimmer/controller, LED driver with 1-10V input, low-voltage control cable, compatible LED light sources
Commercial spaces that require central and local control, applications that prefer physical push buttons and precise dimming	LED driver/controller with 1-10V and push-dim inputs, 1-10V dimmer/controller, momentary push button, low-voltage cabling, compatible LED light sources
LED flex stripes, various LED applications requiring precise/consistent dimming, color mixing.	PWM dimmers/controllers (often integrated), LED drivers (PWM-compatible or integrated), LED light sources
Residential, commercial, recessed under cabinet lights, accent lighting.	LED controller/driver with PWM output and push dim input, momentary push button, compatible LED light sources
Residential, commercial, retrofit, exterior/hard-to-access luminaires	RF transmitter (remote control/switch), RF receiver (often integrated), dimmable LED light sources that are compatible with the RF system.
Residential/commercial applications where both remote and local control is required.	RF transmitter (remote control), RF receiver with push-dim input, momentary push button, compatible LED light sources
Large commercial buildings, smart homes with extensive automation, projects that require integrated control.	KNX bus power supply, KNX control devices, KNX LED dimming actuators, KNX-compatible LED drivers/luminaires, KNX bus cabling.
Residential/commercial areas where basic dimming with standard switches is required.	LED light sources with integrated step dimming function, standard on/off switch.
Generally not recommended for LEDs, may occur unintentionally with incompatible dimmers.	Voltage reduction device (resistance, incompatible dimmer), LED light source

4. Important considerations when choosing the right dimming method

Selecting the appropriate dimming method for LED lighting requires careful consideration of several key factors to ensure optimal performance, compatibility and user satisfaction.

Compatibility:

Ensuring the compatibility of all components of the dimming system is of the utmost importance. The dimmer, the LED driver (if used) and the LED light source must be designed to work together. Incompatibility can lead to a number of problems, including flickering lights, humming noises, a limited dimming range where the lights do not dim down as expected, or even damage to the LED light or the dimmer itself. It is always advisable to consult the manufacturer's specifications and compatibility lists for both the dimmer and the LED product to ensure that they are designed to operate correctly together.

Potential problems:

Various common problems can occur when dimming LEDs**. Flickering** is a common problem, often caused by the use of an incompatible dimmer, the use of inferior LEDs, exceeding the load limits of the dimmer or problems with the electrical wiring. Using LED-specific dimmers and ensuring they are compatible with the specific LED load can often eliminate the flicker. **Humming or buzzing** from the dimmer or LED luminaire can also occur, often due to an incompatibility between the dimmer and the electronic ballast of the LED illuminant or sometimes due to loose components in the luminaire. Trying a different dimmer that is known to be compatible with the LED driver can sometimes eliminate this noise. In some cases, LEDs may **exhibit a slight glow even after they have been turned off**. This may be due to residual current in the circuit, especially with certain types of dimmers. If this is a problem, it may be necessary to use a dimmer with a complete switch-off device.

Installation requirements and complexity:

The complexity of the installation varies considerably between the different dimming methods. Simple leading edge/trailing edge dimmers are generally easy to install and often replace a standard light switch. Push button dimming is also relatively simple and often only requires a two-wire connection to the driver. In contrast, systems such as 1-10V dimming require additional low-voltage control wiring, while more advanced systems such as DALI and KNX require more complex wiring and often involve programming and commissioning. For complex installations or in case of uncertainty, it is always recommended to consult a qualified electrician to ensure safety and proper function.

Load type (ohmic, inductive, capacitive):

Understanding the electrical load characteristics of the LED light source and its driver is crucial for selecting a compatible dimmer. Dimmers are often labeled with letters indicating the types of loads they are designed for: ‚R' for resistive loads (such as incandescent lamps), ‚L' for inductive loads (such as some transformers) and ‚C' for capacitive loads (common with LED drivers). Many LED drivers represent a capacitive load. Using a dimmer that is not designed for the specific load type can lead to dimming problems or damage to the components. Trailing edge dimmers (RC) or universal dimmers (RLC) are generally recommended for LED lighting, as they are better suited to the capacitive loads that most LED drivers have.

5. Conclusion

The variety of LED dimming technologies is large and offers a wide range of options for different needs and applications. From the simplicity of leading edge phase/trailing edge phase and push-button dimming to the sophisticated control provided by DALI and KNX and the efficiency of PWM, each method offers its own advantages and considerations. When advising your customers on the most suitable dimming solution, it is crucial to consider factors such as the desired level of control, the complexity of the installation, budget constraints and, above all, the compatibility between the dimmer, LED driver and LED light source.

For uncomplicated residential applications and retrofits, leading edge/trailing edge dimming (especially trailing edge dimming) and push-button dimming offer user-friendly and cost-effective solutions. In commercial environments that require more advanced control, scalability and integration with building management systems, DALI and KNX offer robust and feature-rich options. PWM dimming stands out as a highly effective technology for LED strips and applications where consistent color and a wide dimming range are of the utmost importance. Hybrid approaches such as „DALI or push" and „1-10V and push" offer improved flexibility by combining different control interfaces. Simpler methods such as step dimming can provide a basic dimming function without the need for dedicated dimmers, while voltage reduction is generally not recommended for modern LED lighting.

Ultimately, the optimal choice of dimming method depends on the specific requirements of the project. Emphasizing the importance of checking product documentation, consulting compatibility lists and seeking expert advice when unsure will ensure that your customers achieve reliable and satisfactory LED dimming results and realize the full potential of their LED lighting investment in terms of energy savings, ambience creation and extended service life.