

Phase-cut dimmer for LED lamps with a uniform dimming function

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ABSTRACT

Now LED lamps have become the dominant light source in lighting systems due to their high luminous efficiency and longer service life. The development of information technology has led to the popularization and widespread implementation of various smart devices, including smart lighting systems. In this regard, the demand for brightness control of LED light sources is also increasing. This article considers the features of brightness control for LED lamps powered by AC, the problems that arise in this case, analyzes their main causes. The main attention is paid to the phase-cut dimming method, an approach to its application for brightness control is considered, which ensures a change in brightness in accordance with its human perception, a dimmer circuit for its implementation is proposed.

Keywords: LED lamps, brightness control, dimmer, phase-cut dimming, uniform change of LED brightness

1. INTRODUCTION

Lighting control is used to reduce energy consumption and create comfortable lighting in a room or workplace. Modern approaches to lighting control are based on controlling the brightness of light sources, which allows not only to change the intensity of lamplight, but also to control its color temperature, obtain the desired artistic effect, etc.¹.

Currently, light sources based on LED technology are most widely used in lighting systems. An LED is a semiconductor device designed for use in low-voltage DC electrical circuits. Therefore, the connection of an LED light source to an AC network is carried out through a special device - an LED driver, which converts the input AC voltage to low-voltage DC voltage and provides a given value of the LED constant current. It is the driver that determines the ability to control the brightness of the LED light source.

There are many types of LED drivers and many specialized integrated circuits that are used to build them. Despite this, two main types of drivers can be distinguished: with a constant output voltage and a constant output current^{2,3}. Not so long ago, direct AC LED driver topologies were developed that allow you to do without the use of bulky inductive components, and therefore are characterized by smaller dimensions and cost compared to the traditional topology based on a diode bridge rectifier and a pulsed DC-DC converter. As a rule, they are built on the basis of specialized integrated circuits or using operational amplifiers⁴.

The driver of a usual LED lamp powered by an AC network is designed to provide the rated DC current of the LEDs regardless of the input voltage fluctuations within a given range. Therefore, the possibility of controlling the brightness is supported only by special LED lamps with a dimming function. In order for an LED lamp to be dimmable, the lamp driver must interpret the dimmer output signal to adjust the DC current of the LEDs. In this regard, much research is being conducted, covering both dimmable AC-DC and DC-DC drivers, as well as various phase and PWM dimming schemes⁵.

2. PROBLEMS OF COMBINING DIMMERS AND DIMMABLE LED LAMPS

The brightness of the light source is controlled by dimmers. In the case of an LED light source, the dimmer is connected between the AC network and the LED driver. Today, the main methods of dimming LED lighting are^{6,7}: phase-cut, pulse-width modulation (PWM), analog 0-10 V and digital using the DALI (Digital Addressable Lighting Interface)

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protocol. In any case, the brightness of the LEDs is changed using amplitude modulation (AM) or PWM^{3,8,9}. In the first case, the direct current of the LEDs changes directly, in the second, the LEDs operate in a cyclic on-off mode, in which the current imposed on the LED is rectangular pulses with a nominal amplitude and a variable duty cycle.

Among the various methods of dimming LED lamps, only phase dimming, which is based on cutting off part of the network sine wave, does not require the use of separate signal lines between the dimmer and the LED driver. This makes it possible to directly apply it in existing lighting systems in which usual incandescent lamps are replaced by LED ones. It should be noted that it is not always possible to achieve full compatibility of the dimmer and LED lamp with the phase dimming function, which is manifested in slow lamp start-up, uneven glow and flickering, limited brightness adjustment range, and humming of the lamp driver^{10,11,12}.

The above problems are related to the fact that the most common phase dimmers use a triac as a control element. Such dimmers cut off the leading part of the half-wave (Leading Edge Dimming) (Fig. 1a). Since the lamp driver is a reactive load for the dimmer, significant current or voltage surges are formed at the moment the triac is turned on, especially if the switch-on occurs at a time when the mains voltage has an extreme value (50% root-mean-square (RMS) voltage of the waveform). In addition, in the final phase of the half-wave, when the mains voltage approaches zero, the LED current is insufficient to keep the triac in the on state. This causes the triac to close prematurely. As a result, flickering may occur at low brightness levels, and the minimum possible brightness level is too high. Therefore, phase dimmers in which one or two transistors are used instead of a triac are better suited for LED lamps. Such dimmers cut off the trailing half-wave (Trailing Edge Dimming), which is better suited for reactive loads (Fig. 1b). But even in this case, the problem of dimmer and lamp compatibility may not be completely solved^{13,14,15}.

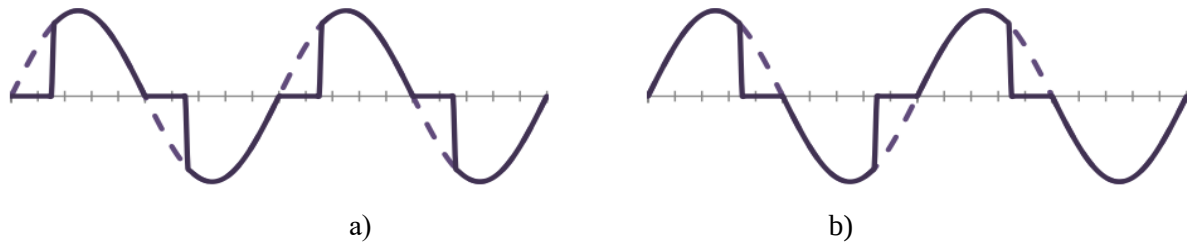


Figure 1. Phase-Cut dimming: a) Leading Edge; b) Trailing Edge

Another problem with phase dimming is to provide uniformity in brightness control. Uniformity is understood as a change in brightness that corresponds to the natural human perception of relative brightness. Most manufacturers try to make dimmers linear. Linearity in brightness control simplifies matching the dimmer with different light sources. However, human perception of brightness is nonlinear. As a result, linear dimming has high sensitivity of control at low brightness values, but low sensitivity at high values. Therefore, dimmers that can provide more natural dimming seem more promising.

3. METHOD OF PHASE-CUT DIMMING WITH UNIFORM BRIGHTNESS CHANGE

In order for a change in brightness to be perceived as uniform, the brightness must change in accordance with the Weber-Fechner law, according to which¹⁰ to detect a change in the stimulus, a constant percentage must be added to its value. In other words, the larger the stimulus, the larger the increment that should be added in order for a minimal change to be noticed. Mathematically, this can be written as

$$\psi = \frac{B_{i+1} - B_i}{B_i}, \quad (1)$$

where ψ is some constant;

$B_{i+1} - B_i$ is the smallest difference in brightness that allows us to distinguish the new brightness B_{i+1} from the previous B_i .

It is known that the brightness of the LED is proportional to the direct current flowing through it. Then, taking into account expression (1), the change in brightness will be perceived as uniform, that is, natural, if the current of the LEDs of lamp changes so that its new value is related to the previous one as:

$$I_{i+1} = I_i(m + 1) = m'I_i, \quad (2)$$

where m' is a constant that takes into account both the human feel of light and its relationship to the level of external illumination, as well as the ratio between the brightness and the direct current of the LED.

Our experiments with 1 W LEDs with different color temperatures under different external lighting conditions have shown that the change in illumination of a white sheet of paper created by an LED becomes notable with an average change in LED current of 6–9%, which corresponds to m' values from 1.06 to 1.09. At lower values, it is impossible to notice the difference in illumination. In dimmers with manual control, it seems advisable to take m' greater than 1.06 to simplify the user's selection of the desired illumination level.

From formula (2) it follows that if the driver of a dimmable LED lamp is a converter of the average voltage $\bar{V}_{in}$ at its input into the LED current I' , that is, if the transmitting characteristic of the driver is defined as

$$I' = K\bar{V}_{in}, \quad (3)$$

to feel a uniform change in brightness, the average voltage at the driver input must change so that

$$\bar{V}_{i+1} = m'\bar{V}_i. \quad (4)$$

When the adjustable parameter of the dimmable LED lamp driver is the voltage across the LEDs, the situation changes. The current I of the LED depends on the voltage V on it in the same way as in a conventional diode:

$$I = I_0 \left(e^{\frac{qV}{kT}} - 1 \right),$$

where I_0 is the reverse current; q is the electron charge; k is the Boltzmann constant; T is the absolute temperature.

The threshold voltage of the LED, at which the LED starts to emit light, is much higher than kT/q . In this case, $\exp[kT/q] \gg 1$, and therefore forward current of the LED is

$$I = I_0 e^{\frac{qV}{kT}}. \quad (5)$$

Taking into account (5), formula (2) takes the form:

$$I_0 e^{\frac{qV_{i+1}}{kT}} = m' I_0 e^{\frac{qV_i}{kT}},$$

or

$$e^{\frac{qV_{i+1}}{kT}} = e^{\left[\frac{qV_i}{kT} + \ln m' \right]}.$$

From here

$$V_{i+1} = V_i + B, \quad (6)$$

$$\text{where } B = (kT/q) \ln m'. \quad (7)$$

Thus, since the driver of a dimmable LED lamp converts the average voltage $\bar{V}_{in}$ at its input to the voltage V' on the LEDs, i. e. if the transmitting characteristic of the driver is defined as

$$V' = K\bar{V}_{in}, \quad (8)$$

to feel a uniform change in brightness, the average voltage at the driver input according to (6) taking into account (8) should change so that

$$\bar{V}_{i+1} = \bar{V}_i + B/K, \quad (9)$$

where B is defined by formula (7).

With phase-cut trailing edge dimming, the average voltage at the driver input per half period is

$$\bar{V}_i = \frac{2}{T} V_m \int_0^{t_i} \sin\left(\frac{2\pi}{T} t\right) dt = \frac{V_m}{\pi} \left[1 - \cos\left(\frac{2\pi}{T} t_i\right)\right], \quad (10)$$

де V_m is the amplitude value of the mains voltage; T is the period of the mains voltage; t_i is the moment of cutting off the mains voltage during phase-cut trailing edge dimming.

If the driver of dimmable LED lamp is a voltage-current converter with a transmitting characteristic similar to (3), for a uniform change in brightness, the new time point t_{i+1} of the AC voltage cut-off must be such that equality (4) is satisfied

$$\frac{V_m}{\pi} \left[1 - \cos\left(\frac{2\pi}{T} t_{i+1}\right)\right] = m' \bar{V}_i.$$

From here we find the new time point t_{i+1} for phase-cut trailing edge dimming, when the driver of the dimmable LED lamp is a voltage-current converter:

$$t_{i+1} = \frac{T}{2\pi} \arccos \left[1 - \frac{\pi}{V_m} m' \bar{V}_i\right]. \quad (11)$$

If the driver of dimmable LED lamp is a voltage-voltage converter with a transmitting characteristic similar to (8), for a uniform change in brightness, the new time point t_{i+1} is determined by the equality (9):

$$\frac{V_m}{\pi} \left[1 - \cos\left(\frac{2\pi}{T} t_{i+1}\right)\right] = \bar{V}_i + \frac{B}{K}.$$

From here we find the new time point t_{i+1} for phase-cut trailing edge dimming, when the driver of the dimmable LED lamp is a voltage-voltage converter:

$$t_{i+1} = \frac{T}{2\pi} \arccos \left[1 - \frac{\pi}{V_m} \left(\bar{V}_i + \frac{B}{K}\right)\right]. \quad (12)$$

Cyclically using formulas (10) and (11) (when the driver of dimmable LED lamp is a voltage-current converter), or (10) and (12) (when the driver of dimmable LED lamp is a voltage-voltage converter), it is possible to determine all time points for phase-cut trailing edge dimming in the interval from 0 to $T/2$, which will ensure a uniform change in the brightness of the LED lamp in the range from 0% to 100%. It should be noted that in the case when the driver is a voltage-current converter, the initial condition $t_0 = 0$ is not acceptable. With such an initial condition $V_{i=0} = 0$ (formula (10)). Therefore, for t_1 , according to formula (11), we also obtain 0. From hence for the driver of the LED lamp, which converts voltage into current, it is advisable to choose $t_0 = T/2$ as the initial condition, i.e., to perform the calculation according to the decrease in brightness (in formula (11), use $1/m'$ instead of m').

The general scheme of a universal dimmer, which allows implementing the considered approaches to phase-cut trailing edge dimming, is shown in Fig. 2.

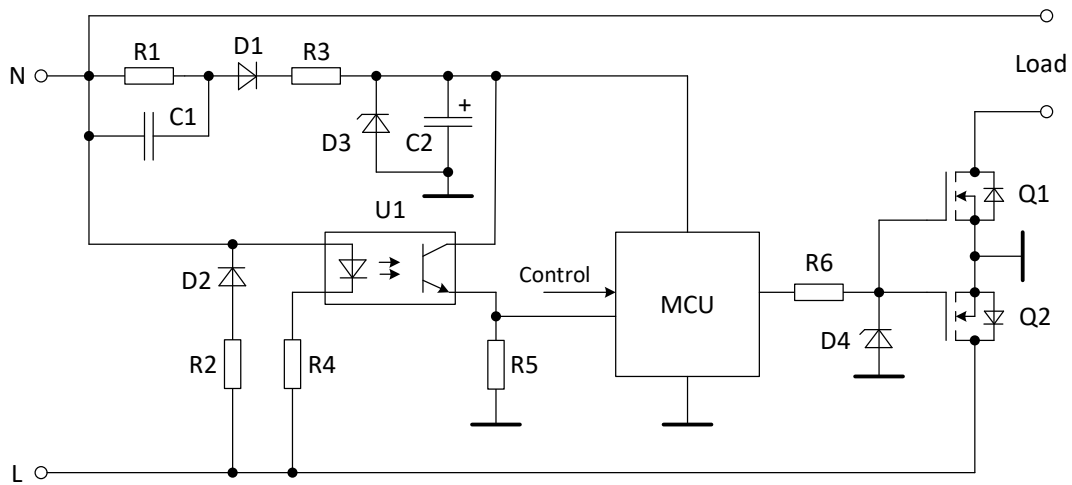


Figure 2. Trailing edge dimmer schematic

Dimmer is built on a universal microcontroller that provides phase-cut trailing edge dimming. The delay of cutting off a part of the sine wave of the mains voltage to set the desired value of the brightness of the LED lamp is taken from an array of values stored in the microcontroller's memory. The elements of the array are values calculated using the method discussed above. Control of brightness can be carried out using a touch, key or rotary element. Using a microcontroller also allows you to implement brightness control via WiFi or Bluetooth.

To power the microcontroller, a simple half-wave rectifier on a diode D1 and a linear voltage regulator on a Zener diode D3 with a resistor R3 are used. Capacitor C1 is used to limit the current. A resistor can be used instead of a capacitor. This will reduce phase interference, but increase power dissipation.

The optocoupler U1 is the zero-crossing detector, which gives a pulse at the microcontroller input when the mains voltage is negative. Diode D2 protects the optocoupler LED from breakdown, limiting the reverse voltage on it. The power switch is built on back-to-back n-channel power MOSFETs Q1 and Q2. When the MOSFETs are conducting, a circuit is formed for the flow of current from the Line (L) via Q1, Q2 and the load to the Neutral (N). When the MOSFETs are closed, the current required to power the circuit elements flows during the negative half-cycle of the mains voltage from Neutral to Line via the internal diode in Q2. Zener diode D4 limits the voltage at the gates of the MOSFETs.

4. CONCLUSION

Usual phase-cut TRIAC dimmers do not allow achieving high-quality brightness control of LED lamps, which manifests itself in lamp flickering, a limited control range, and the inability to achieve a low level of dimming. More suitable for these purposes are phase-cut trailing edge dimmers, which use MOSFETs for phase-cut. At the same time, the compatibility issues of the dimmer and the LED lamp driver remain unresolved. This is manifested to the fact that different lamps are dimmed differently by the same dimmer. The proposed phase-cut microcontroller dimmer allows to control brightness in accordance with the natural perception of brightness changes by a human and can be used to dim dimmable LED lamps with drivers of different types. The latter is implemented by simply switching the microcontroller software to use other values by which the microcontroller determines the moments for phase-cut. The use of a microcontroller also makes the dimmer independent of how interaction with it is implemented and makes it possible to implement almost any lighting control algorithm.

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