

Analysis of supply parameters of single- and double-string LED lamps with integrated AC direct capacitorless drivers

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Abstract. Thanks to a very high luminous efficacy of LED lamps (over 160 lm/W) they are the most preferred light sources in lighting applications today. The useful lifetime of LED modules exceeds 50,000 hours. Chromatic parameters of lamps making use of SSL (Solid State Lighting) have already equalled classic solutions, although they were noticeably worse not so long ago. High values of the Colour Rendering Index (CRI) and ease of control over the luminous flux cause that lamps with LEDs have become very attractive solutions. Today, the most important problem concerns LED drivers supplied from the 230 VAC mains. The lifetime of switched-mode converters, including electrolytic capacitors, is considerably shorter than that of LEDs. This paper discusses the features of alternative drivers for LED modules which are supplied directly from the 230 VAC mains and do not contain any electrolytic capacitors. In particular, power factor and efficiency of lamps with one or two LED strings are analysed and some hints concerning optimal design of such lamps are given. A unique feature of this work is a detailed analysis of harmonics contents in the supply current of such drivers, proving their conformity with the relevant standard. Finally, some problems associated with flicker resulting from the considered type of supply are mentioned.

Key words: SSL, LED, LED-COB, PWM, power factor, efficiency, flicker, SM2082, LED AC direct driver.

1. Introduction

High brightness LEDs (Light-Emitting Diodes) have been dominating lighting applications thanks to their advantages such as high efficiency of light generation (over 160 lm/W), ease of control over both colour and intensity of the generated light and long lifetime, exceeding 50,000 hours. However, in contrast to conventional sources of light such as incandescent lamps and CFLs (Compact Fluorescent Lamps), which can be easily supplied from the 230 V 50 Hz mains, a single LED must be supplied from a low value DC voltage source. What is more, LEDs can conduct current in one direction only and due to the high steepness of the current versus the voltage curve in the conduction mode, they have to be supplied with constant current rather than constant voltage. Another specific feature of LEDs is their very fast response to the change of the supply current. This feature is very attractive from the point of view of using LED lamps, apart from illumination, for transmission of data at a high speed, which is known as VLC (Visible Light Communication). However, in lighting applications, the fast current to light response of LED lamps may contribute to increased flicker at double the mains frequency, more intensive than with other types of lamps, unless good stabilization of the AC rectified voltage is guaranteed.

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2. AC drivers for LED lighting

The drivers for LED modules which are supplied from the 230 VAC mains must satisfy a number of important requirements. First of all, legal regulations concerning lighting installations impose the minimum value of the power factor (PF), making it dependent on the electric power of the lamp [1, 2]. Today, in the most restrictive variant of such regulations the power factor must be greater than 0.9 (when $P_{lamp} > 25$ W) [1], but for lower power values it is allowed to be significantly smaller (0.4–0.7). As the LED lamp is a greatly nonlinear load, the current drawn from the mains by its driver is often distorted, so the harmonics contents must conform to relevant regulations. To minimize flicker, the ripple of the rectified mains voltage should be considerably reduced. The designs of supply systems must also provide sufficient immunity to overvoltages that often appear in the 230 VAC mains as a result of commutation of large loads or lightnings.

LED drivers are basically divided into the passive and active ones (Fig. 1). Their thorough overview is included in [3, 4]. However, in [3] hardly any references are provided to papers published later than in 2012, while a very recent overview [4] is concentrated on flicker-free solutions.

In low-cost, low-power, passive drivers the mains voltage is rectified and filtered with an electrolytic capacitor. The obtained DC voltage is applied to a string of LEDs, with a total conduction voltage of at least tens of volts, through a current limiting resistor or current regulator. Sometimes a step-down transformer or a series capacitor is used to reduce the line voltage. Passive drivers are usually used for LED lamps with the nomi-

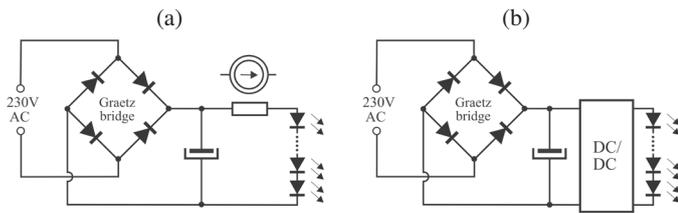


Fig. 1. Passive (a) and active (b) LED drivers

nal power up to 25 W [4]. It is worth noticing that a 25 W LED lamp is a source of considerably stronger light than a 150 W incandescent lamp, which was usually the most powerful conventional lamp with the base E27 for residential applications. For LED lamps and luminaires rated for the power from about a dozen to tens of watts, which are supplied from 230 V AC, active drivers are usually used, which are based on an AC rectifier and a switched-mode DC/DC converter with the output characteristic of the *constant current* type. In order to increase the power factor of such converters they are often supplemented with an active power correction factor (PFC) circuit. The complete supply circuit of such a type, often incorporating a PWM controller of light intensity, circuitry for colour change and possibility of remote control, takes up quite a lot of space. Due to the use of electrolytic capacitors, whose lifetime is nominally up to 10,000 hours only comparing to more than 50,000 hours for LEDs, the durability of the driver is much shorter than that of the LEDs. At temperatures that may exceed 100°C inside an LED lamp the lifetime of electrolytic capacitors is further considerably reduced. The use of electrolytic capacitors to reduce the ripple of the rectified AC voltage is not a problem as long as the LED driver is a separate unit, because in case of its failure it can be easily replaced, leaving the LED installation intact. The problem of the elevated temperature inside an LED lamp would also concern core inductors, which are necessary components of switching converters, if such converters were to be integrated inside the lamp.

The situation, in which LED drivers were designed mainly as separate units, has considerably changed since manufacturers started widely offering LED lamps as energy-saving substitutes for incandescent bulbs with the E14 and E27 bases. There is a large variety of IC drivers commercially available for such applications. They are based on switched-mode converters and due to the need for electrolytic capacitors they suffer from premature failure, so the lifetime expected for the LEDs themselves can never be even approached for the lamp as a whole, which cannot be disassembled for replacement of the driver. Although many new solutions of sophisticated switched-mode drivers have been recently developed, whose main idea is to replace the electrolytic capacitors with non-electrolytic ones and miniaturize the supply driver, they can often hardly fit into the limited space inside an LED lamp designed as a substitute for a conventional bulb and they considerably increase the cost of the lamp. Another problem with LED drivers based on switched-mode drivers is RF emission that may disturb the operation of the nearby radio equipment. A simple and low-cost alternative solution that allows eliminating both electrolytic capacitors and

inductors was proposed at the beginning of the 2010s and is sometimes referred to as AC direct drivers for multiple-string LED lamps.

2.1. AC direct drivers for LED lamps. The idea of such drivers has been explained in detail in [5–13]. The simplest version is shown in Fig. 2. To obtain the power factor very close to 1 in circuits with no reactive components, there should be a linear relationship between the supply voltage and current, that is $i_{\text{sup}}(t) = k \cdot u_{\text{sup}}(t)$ or, according to the figure, $i_{CS} = k \cdot u_R$. In turn, to ensure low power loss in the current regulator, the number n of LEDs connected in series should be dynamically changed depending on the instantaneous value of the rectified AC voltage u_R . A possibly small voltage drop kept across the current regulator over the whole period of the mains voltage will guarantee high luminous efficacy of the lamp.

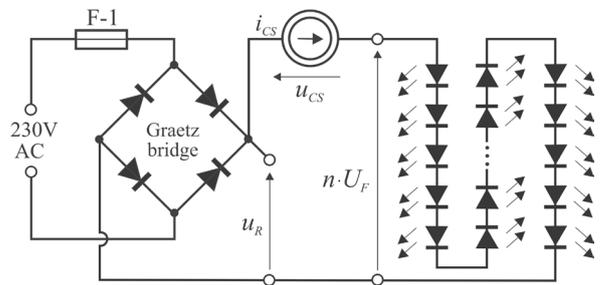


Fig. 2. Circuit diagram of a simple LED lamp supplied from 230 V AC

In order to dynamically change the number of LEDs connected in series, a structure shown in Fig. 3 is proposed in [5–10, 12]. The rectified mains voltage is applied directly to several strings of LEDs. When this voltage reaches the conduction voltage U_1 of the first string, the switch S1 closes and the current starts flowing. Upon reaching the conduction voltage for both the first and the second string, $U_1 + U_2$, S1 opens and S2 closes and so on until all strings are connected in series. With the rectified voltage decreasing, the switches are switched over in reverse direction. The current is shaped as a staircase waveform in order to make it resemble a sine wave. However, such drivers require complicated circuitry, realized

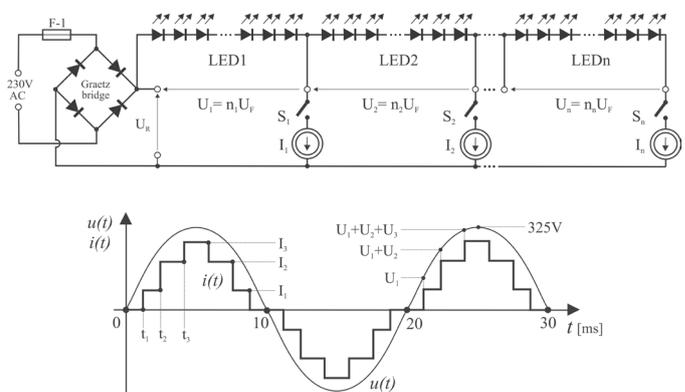


Fig. 3. Simplified circuit diagram of a multi-string AC direct driver and waveforms of the supply voltage and current

as integrated circuits specifically designed for particular applications.

The main deficiency of the published descriptions of multi-string LED drivers is that they do not include any analyses showing how the efficiency and power factor are dependent on the number of strings and the number of diodes in each string that could provide hints concerning an optimum choice of these numbers. The number of strings, which is usually 3–6, is given arbitrarily and the number of LEDs in each string is hardly ever stated [14]. Instead, the authors concentrate on describing the structure of their IC drivers and the results of their simulations to prove that the obtained power factor and efficiency are better than in others' designs.

The turn-on (conduction) voltage U_F of white LEDs is usually within 2.8–3.2 V, so the total number of LEDs could approach 100. This would greatly increase the assembly time of a lamp and decrease its reliability. Instead of single LEDs most often the so called Chip On Board (COB) diode modules or triple LEDs (3 luminophore-coated chips in a small SMD package) are used. Due to this fact, the number of possible sequences of LEDs connected into strings is reduced. However, this limits the possibility of achieving the optimum values of the power factor and luminous efficacy to a small degree only.

In practical realizations one or several switched LED strings are used. The designers of drivers for lamps with multiple strings claim that very good electrical parameters of LED lamps with dedicated experimental, rather than commercial, integrated circuit drivers can be obtained, for example $PF > 0.98$ and high efficiency (greater than 90%) of the supply system, which is defined as:

$$\eta = \frac{P_{LED}}{P_{lamp}} \cdot 100\%, \quad (1)$$

where P_{LED} is the electric power drawn solely by the LEDs and P_{lamp} is the total power delivered to the lamp. It is worth mentioning that there is, in fact, no need for a very high value of this efficiency. The luminous efficacy of LEDs available on the market today exceeds 150–160 lm/W. The total luminous efficacy of a lamp is a product of the luminous efficacy of LEDs themselves and the electrical efficiency of the supply circuit. Even if the electrical efficiency drops to, say, 60%, the LED lamp still remains one of the most energy-saving light sources supplied from the 230 VAC mains. The efficiency of the supply circuit has no crucial effect on the operating temperature of the lamp. The electrical efficiency of LEDs, understood as the ratio of the power of the electromagnetic wave (light) emitted by the diode to the consumed electric power, is about 30–40% today and it further decreases with the operating temperature, as has been proved experimentally, e.g. in [15]. This means that even in a lamp with its supply circuit 100% efficient, at least 60–70% of electric energy would be converted into heat. It should be also mentioned that due to aging luminous efficacy of LEDs deteriorates and, in consequence, their electrical efficiency also decreases, which results in an additional rise in the operating temperature. Therefore, while designing the heat sink for an LED module it is reasonable to assume that the whole electric power consumed will be converted to heat.

3. Electrical parameters of LED lamps

The simplest example of an LED lamp directly supplied from the 230 VAC mains is a lamp with a single string of diodes and a constant current regulator (Fig. 4). It turns out that even such a simple design allows achieving good values of the power factor with acceptable total luminous efficacy, although it seems that many lamps available on the market are not optimally designed. The waveforms explaining the operation of such a lamp are shown in Fig. 5. The optimization of lamp parameters in this case consists of choosing the optimum moment t_1 , from the range 0–5 ms, at which a constant current I_{CS} starts flowing through the LED string. In fact, this time is dependent on the number n of diodes in the string according to the relationship $u_R(t_1) = n \cdot U_F + U_{CSmin}$, where U_{CSmin} is a minimum voltage drop across the current regulator at which it starts operating properly. The voltage drops across rectifier diodes in circuits supplied from 230 VAC are usually negligible and $n \cdot U_F$ is much greater than U_{CSmin} , so we can assume that $u_R(t_1) \approx n \cdot U_F$ and the optimum length of the LED string may be finally determined from this relationship. The power delivered to the LEDs (assuming that $U_{CSmin} \approx 0$) and the total power drawn by a lamp with a single string of diodes from the 230 VAC mains as a function of t_1 (assuming that $U_{CSmin} \approx 0$) are given by the following relationships:

$$P_{LED} = \sqrt{2} \cdot 230 \text{ V} \cdot I_{CS} \cdot \frac{4}{T} \int_{t_1}^{T/4} \sin \omega t_1 dt = \sqrt{2} \cdot 230 \text{ V} \cdot I_{CS} \cdot \left(1 - \frac{4}{T} t_1\right) \cdot \sin \omega t_1, \quad (2)$$

$$P_{lamp} = \sqrt{2} \cdot 230 \text{ V} \cdot I_{CS} \cdot \frac{4}{T} \int_{t_1}^{T/4} \sin \omega t dt = \frac{2\sqrt{2} \cdot 230 \text{ V} \cdot I_{CS}}{\pi} \cdot \cos \omega t_1, \quad (3)$$

where ω and T are the angular frequency and period, respectively, of the mains voltage.

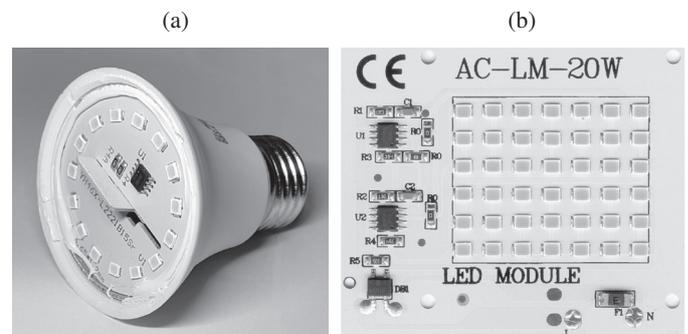


Fig. 4. Inside of a 10 W LED lamp with a single diode string and a current regulator (a) and a 20 W LED module with a single diode string and two current regulators for an illuminator (b)

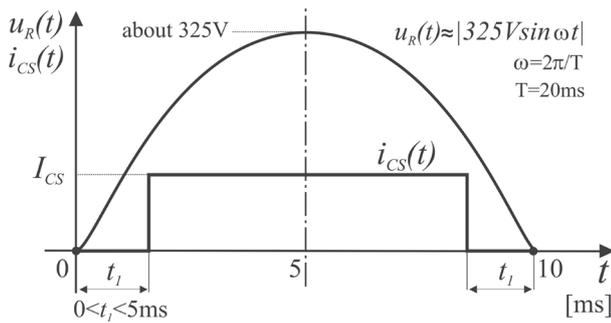


Fig. 5. Waveforms of the supply voltage and current of a single-string LED lamp

Finally, the efficiency of the supply circuit for the lamp, defined in (1), becomes:

$$\eta = \frac{P_{LED}}{P_{lamp}} \cdot 100\% = \omega \cdot \left(\frac{T}{4} - t_1 \right) \cdot \tan \omega t_1 \cdot 100\%. \quad (4)$$

The power factor is the following function of t_1 :

$$PF = \frac{P_{lamp}}{U_{rms} \cdot I_{rms}} = \frac{\sqrt{2} \cdot 230 \text{ V} \cdot I_{CS} \cdot \frac{4}{T} \int_{t_1}^{T/4} \sin \omega t dt}{230 \text{ V} \cdot I_{CS} \sqrt{\frac{4}{T} \int_{t_1}^{T/4} dt}} = \frac{2\sqrt{2} \cos \omega t_1}{\pi \sqrt{1 - 4 \frac{t_1}{T}}}, \quad (5)$$

where U_{rms} and I_{rms} mean the RMS values of the mains voltage and current.

Graphical representation of the functions determined above is shown in Fig. 6.

The optimum values of t_1 determined for each described parameter are significantly different, for example, the maximum value of the power factor PF (0.961) is reached at t_1 equal to 1.29 ms and the efficiency of the supply circuit becomes only 50% then. The current regulator will not be used optimally in this case. In order to obtain the power of the emitted light as large as possible (P_{LEDmax}), when the only limitation results from the maximum manufacturer's current rating for the series current regulator I_{CSmax} , the optimum value of t_1 should become 2.26 ms, which will result in increasing the efficiency of

the supply circuit to a desirable value of about 74% and the power factor will still satisfy even the most rigorous requirements, i.e. $PF(t_1 = 2.26 \text{ ms}) = 0.922$. However, the power factor should be considerably above 0.9 in order to satisfy this requirement in all operating conditions for the LED lamp declared by its manufacturer (wide range of temperature, variations of the supply voltage). It is also important to analyse how the manufacturing spread of the parameters of components used in the lamp affects its performance. This concerns, in particular, the spread of the conduction voltage in the used series of LEDs and its temperature coefficient. In practice, in all known solutions of AC direct drivers for multi-string LED lamps, the moments of turning on individual strings in a proper sequence (i.e. t_1, t_2, \dots, t_n) are determined on the basis of the instantaneous value of the rectified 230 VAC mains voltage. Therefore, the variation of the LED conduction voltage directly affects the actual moments of switching, which, in turn, influence the values of the previously calculated parameters of the LED lamp.

Using the same assumptions as previously ($u_r(t) \approx |325 \text{ V} \sin \omega t|$ and $U_{CSmin} \approx 0$), the number of LEDs, connected in series, required to turn on the current I_{CS} at the moment t_1 can be found from the following formula:

$$n = \frac{\sqrt{2} \cdot 230 \text{ V} \cdot \sin \omega t_1 - U_{CSmin}}{U_F} \approx \frac{\sqrt{2} \cdot 230 \text{ V} \cdot \sin \omega t_1}{U_F}, \quad (6)$$

where U_F is the conduction voltage of LEDs at $I_F = I_{CS}$.

4. Lamp with two LED strings

The most significant disadvantage of the previously described simple LED lamp with a single string of diodes is a low efficiency of its supply circuit, which becomes 50% at the optimum value of the power factor ($PF = 0.961$ at $t_1 = 1.29 \text{ ms}$). A simple method of increasing the efficiency of the supply circuit, that will not deteriorate the power factor, is to introduce an additional string of n_2 LEDs connected in series with the basic string (n_1 LEDs). The idea of this solution is presented in Fig. 7.

The additional string is bypassed by a normally closed switch (S_{ON}), which becomes open (S_{OFF}) at t_2 and closed back at $T/2 - t_2$ over each half-cycle of the supply voltage. Thanks to

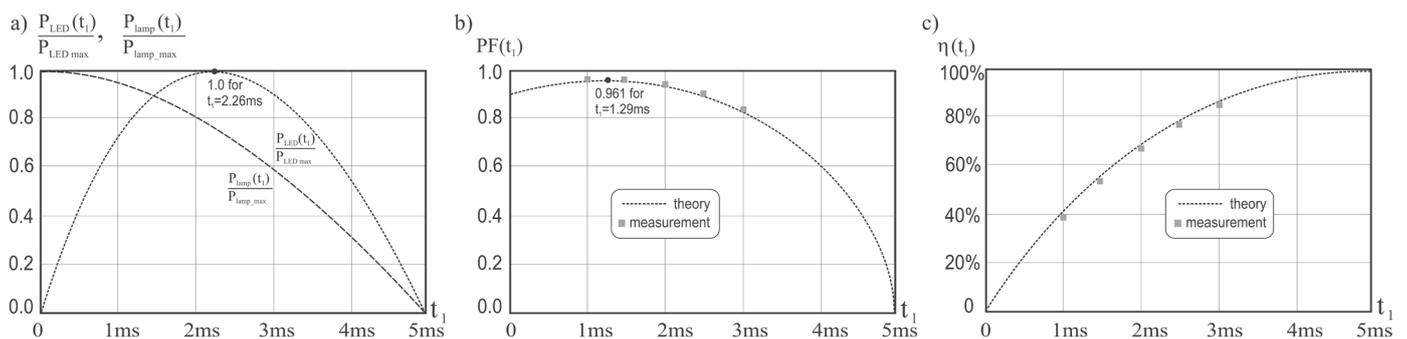


Fig. 6. Plots of the normalized power P_{LED} and P_{lamp} (a), power factor PF (b) and efficiency of the supply circuit η (c)

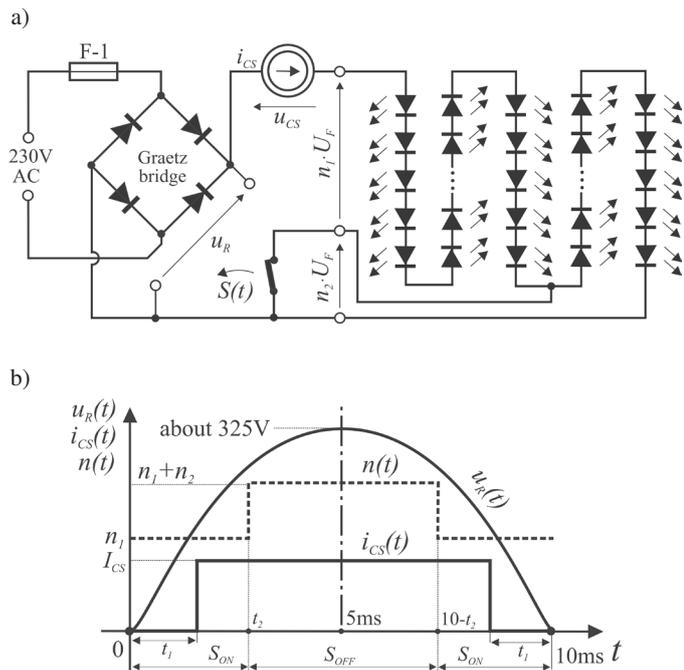


Fig. 7. Lamp with two strings of LEDs: a) simplified circuit diagram, b) waveforms illustrating operation of the lamp and the switch S(t), which connects and disconnects the second string

that the total number of LEDs increases ($n = n_1 + n_2$) in the interval from t_2 to $T/2 - t_2$, when the mains instantaneous voltage reaches high values. In consequence, within this time interval the voltage drop across the current regulator (u_{CS}) decreases, thanks to which both the electrical efficiency and the luminous efficacy of the lamp increase. The moment t_2 must obviously be included between t_1 and $T/4$.

The optimum value of t_2 should be determined so that the efficiency of the supply circuit becomes possibly high. It is worth mentioning that if the currents flowing through t or

both diode strings are the same, the waveform of the supply current drawn from the mains does not change either (Fig. 5 and Fig. 7b). The power factor also remains the same (e.g. 0.961 at $t_1 = 1.29$ ms). The efficiency of the supply circuit for a lamp with two LED strings is given by the following equation (assuming that $U_{CSmin} \approx 0$):

$$\eta = \frac{\sqrt{2} \cdot 230 \text{ V} \cdot I_{CS} \cdot \frac{4}{T} \left(\int_{t_1}^{t_2} \sin \omega t_1 dt + \int_{t_2}^{T/4} \sin \omega t_2 dt \right)}{\sqrt{2} \cdot 230 \text{ V} \cdot I_{CS} \cdot \frac{4}{T} \int_{t_1}^{T/4} \sin \omega t dt} \cdot 100\% = \omega \cdot \left[(t_2 - t_1) \cdot \tan \omega t_1 + \left(\frac{T}{4} - t_2 \right) \cdot \frac{\sin \omega t_2}{\cos \omega t_1} \right] \cdot 100\% \quad (7)$$

Table 1 presents parameters of LED lamps with one or two diode strings. The optimum time t_2 that ensures maximum efficiency of the supply circuit for a lamp with two LED strings has been determined numerically. While taking t_1 as a parameter, the optimum values of t_2 were sought from the range $t_1 - T/4$ for which the formula (7) reaches a maximum. The obtained results prove that it is possible to considerably increase the luminous flux generated by a lamp by a simple circuit modification, that is an inclusion of an additional LED string. When $t_1 = 2.26$ ms (the highest power for the datasheet value of I_{CSmax}), the expected increase in the luminous flux is about 1/5, while for $t_1 = 1.29$ ms (maximum PF) the flux increases by over a half.

Thanks to the increase in the luminous flux it is possible to proportionally reduce the power consumed by the lamp from the mains. This way, the cost of the suggested modification may become negligible in comparison with the cost of saved electric energy over the expected long lifetime of the LED lamp.

A lamp with two different LED strings, supplied with the same current when one or two strings are turned on, seems to

Table 1
Parameters of LED lamps with one and two strings of diodes*

LED lamp with a single diode string				LED lamp with two diode strings		
t_1 [ms]	Power factor PF	Efficiency of the supply circuit [%]	LED1 (basic) string conduction voltage [V]	Optimum value of t_2 [ms]	Efficiency of the supply circuit [%]	LED2 (additional) string conduction voltage [V]
1.00	0.957	40.83	100.5	2.77	74.38	148.2
1.29	0.961	50.00	128.2	2.93	78.42	130.7
1.50	0.959	56.03	147.7	3.03	81.06	117.2
1.70	0.954	61.31	165.6	3.14	83.37	105.7
1.90	0.946	66.19	182.8	3.24	85.50	94.0
2.10	0.934	70.67	199.4	3.35	87.44	83.1
2.26	0.922	73.98	212.0	3.44	88.88	75.0
2.50	0.900	78.54	230.0	3.58	90.84	63.4

* calculated with the following assumptions: $U_{sup} = 230 \text{ VAC}$; $U_{CSmin} \approx 0$; $I_{CS LED1} = I_{CS LED2} = I_{CS}$

be a reasonable trade-off between the complexity of the driver together with the lamp and the possibility of achieving good electrical and luminous parameters. In [13] analyses of other configurations (an LED lamp with one, two or three identical strings) supplied directly from the rectified AC mains voltage in a different way (the current does not change when successive strings are turned on or the current is shaped as a staircase waveform) have been performed.

5. Harmonics of the supply current

The supply current drawn by any receiver connected to the 230 VAC power grid should preferably follow the sine function. Only in this case will the power factor reach the most desirable value, that is $PF = 1$. Any departure from the sine function results in lowering this parameter and presence of harmonic components in the supply current. These harmonics may change the parameters of the grid and affect the operation of other receivers in an adverse way. The allowed limits for harmonic current emissions from electronic equipment to the 230 VAC grid are set by the regulations concerning electromagnetic compatibility. For the purpose of further analysis we will consider the EN IEC 61000-3-2:2019 harmonized standard [16]. In most cases the final stage of designing any devices supplied from the grid is a choice of a proper filtering circuit in order to reduce harmonics of the supply current. However, such an option cannot be considered for the drivers discussed in this paper because, firstly, the filter, by changing the waveform of the supply current, would invalidate the previously derived formulas. Secondly, the idea of AC direct drivers is to avoid the use of large capacitors and inductors that would have to be used in the filter. Therefore, it is necessary for the harmonic currents emitted by such drivers to comply with the relevant legal requirements without any corrective filter.

According to the IEC 61000-3-2 standard, lighting equipment falls under Class C category. The standard does not define any limits for equipment with power rated less than 5 W. Section 7.4.3 defines limits for lighting equipment having a rated power greater than or equal to 5 W and less than or equal to 25 W. As mentioned earlier, most LED lamps meant as replacements for incandescent lamps or CFLs fall within this power range, for which the standard says that the lighting equipment must comply with one of the three sets of requirements.

According to the first set, the harmonic currents must not exceed the values defined for Class D equipment (including e.g. personal computers and monitors, TV receivers). These limits are less restrictive than for Class C, however, in general, it may be still difficult for a rectangular current waveform to comply with them.

The second set of requirements refers, in particular, to the supply current waveform, shown in the standard and also in [4], which is typical for a rectifier with a capacitive filter. The third harmonic current must not exceed 86% of the fundamental current and the fifth is limited to 61%. In addition, the waveform of the input current must reach 5% of its peak value before or at 60° , reach the peak value before or at 65° and not fall below 5%

of the peak value before 90° . The angle values are referenced to any zero crossing of the fundamental supply voltage.

In the last set of requirements the total harmonic distortion *THD* of the supply current must not exceed 70%, and the allowed limits for the harmonics, expressed as a percentage of the fundamental current, are: the second – 5%, the third – 35%, the fifth – 25%, the seventh – 30%, the ninth and eleventh – 20%.

The requirements from the second set are the easiest to comply with and the most often chosen by designers of lighting equipment. It should be noted, however, that these requirements were originally set for discharge lamps (CFLs) and, in the future, they may be changed, or even removed in order to force withdrawal of such lamps from the market. The third set of requirements has been introduced to the standard most recently, so it is likely that the designs satisfying them will be present on the market for the longest time.

The waveform of the supply current drawn by a lamp from the 230 VAC grid may be represented by the Fourier series

$$i(t) = A_0 + \sum_{k=1}^{\infty} (A_k \cos k\omega t + B_k \sin k\omega t), \quad (8)$$

where A_0 is the DC component (average value) and A_k and B_k are the Fourier coefficients. In the circuits shown in Fig. 2 and Fig. 7 $i(t) = i_{CS}(t)$ or $i(t) = -i_{CS}(t)$, depending on the current half-wave of the mains voltage.

The moment t_2 has no effect on the waveform of the supply current and for any value of t_1 the DC component is zero, so the Fourier coefficients can be found as

$$\begin{aligned} A_k &= \frac{2}{T} \int_{-T/2}^{T/2} i(t) \cos k\omega t dt = \\ &= -\frac{2}{T} \int_{-T/2+t_1}^{-t_1} I_{CS} \cos k\omega t dt \\ &\quad + \frac{2}{T} \int_{t_1}^{T/2-t_1} I_{CS} \cos k\omega t dt = 0, \end{aligned} \quad (9)$$

$$\begin{aligned} B_k &= \frac{2}{T} \int_{-T/2}^{T/2} i(t) \sin k\omega t dt = \\ &= -\frac{2}{T} \int_{-T/2+t_1}^{-t_1} I_{CS} \sin k\omega t dt \\ &\quad + \frac{2}{T} \int_{t_1}^{T/2-t_1} I_{CS} \sin k\omega t dt. \end{aligned} \quad (10)$$

As the supply current is described by an odd function, $B_k = 0$ for any $k = 2N$, where N is a natural number, so finally

$$B_k = 4 \frac{I_{CS}}{k\pi} \cos k\omega t_1 \quad (11)$$

for $k = 1, 3, 5, 7, 9, 11, \dots$

THD of the supply current may be found on the basis of PF or directly from the definition

$$THD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_1} = \frac{\sqrt{\frac{4}{T} \int_{t_1}^{T/4} I_{CS}^2 dt - \left(\frac{B_1}{\sqrt{2}}\right)^2}}{\frac{B_1}{\sqrt{2}}} = \sqrt{\frac{\pi^2 \left(1 - 4 \frac{t_1}{T}\right)}{8 \cos^2 \omega t_1} - 1}, \tag{12}$$

where I_{rms} is the RMS value of the supply current and I_1 is the RMS value of its first harmonic. THD is usually expressed in per cent.

Figure 8 shows how THD and normalized amplitudes of harmonics $|B_k/B_1| \cdot 100\%$ change with t_1 . The limit values defined in the third set of requirements of the standard [16] are also marked in the figures (for lamps with a rated power not exceeding 25 W).

The allowed limit is exceeded first by the third harmonic of the supply current (for $t_1 \approx 2.54$ ms, which is above the range that we consider). Analysing the plot in Fig. 8b we can notice that the local maximum of the function $|B_5/B_1| \cdot 100\%$ (point "A" at $t_1 \approx 2.1$ ms) reaches a value very close to the limit of 25%. In order to examine this point accurately, by mathematical analysis of the function $|B_5/B_1| = (t_1)$ we can find that its maximum occurs at

$$t_1 \text{ [ms]} = \frac{20}{\pi} \arctan \left(\sqrt{\frac{13 - 4\sqrt{10}}{3}} \right) \tag{13}$$

and its value equals exactly the allowed limit of 25%. However, for the purpose of the analysis we have assumed a perfectly rectangular waveform of the supply current, while in a real electronic circuit the slopes of the leading and trailing edges are finite. The slopes of a signal's edges affect the amplitudes of its harmonics, especially the higher ones, so we can expect that local maxima of the function $|B_k/B_1|$ obtained by measurements should be smaller than those resulting from calculations.

Figure 9 shows graphically the values of the function $|B_k/B_1| \cdot 100\%$ obtained both from theory and by measurements using a laboratory model of an LED lamp for $t_1 = 2.1$ ms. The

measurements were repeated for all other values of t_1 given in the first column of Table 1. All results of measurements close to the allowed limits were lower than the theoretical values (usually by 0.5 to 1%). In such a situation the actual value of the power factor PF (which is strictly connected with THD) should be slightly greater than the theoretical value and this was confirmed by the measurements (Fig. 6b).

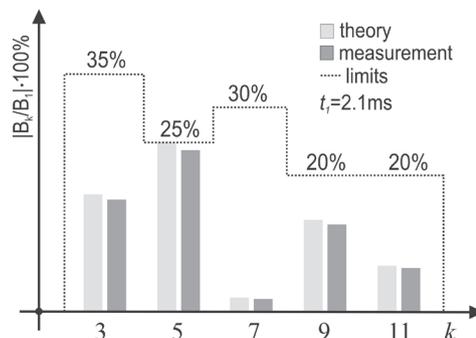


Fig. 9. Comparison of the theoretical and measured values of the function $|B_k/B_1| \cdot 100\%$ for $t_1 = 2.1$ ms

So we can assume that at least for the range $0 \leq t_1 \leq 2.53$ ms the LED lamps presented here, with the rated power not exceeding 25 W, will satisfy the legal requirements concerning the allowed limits for the harmonics of the supply current without any additional filtering circuit.

6. Flicker and other luminous characteristics

Thanks to the possibility of supplying LED lamps directly by the rectified mains voltage, with no need for electrolytic capacitors to filter it, simple and durable LED lamps may be designed. However, the light generated by such lamps cannot be considered as comfortable. Comparing with other sources of light (incandescent and discharge lamps), they are characterized by the highest variability of the luminous flux [17].

Because of the inherent 100 Hz (or 120 Hz in USA) flicker, LED lamps supplied by the AC direct drivers cannot be recommended for prolonged use in residential or professional areas. Nevertheless, they can be a simple and cost-effective alternative in many applications in which this drawback is not so important, for example illumination of communication passages,

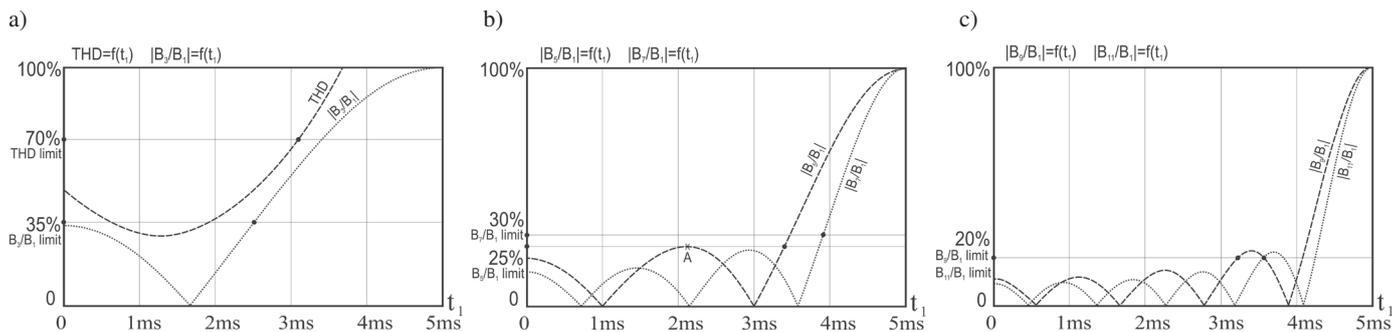


Fig. 8. Plots of percentage THD and $|B_k/B_1|$ as functions of t_1 (allowed limits given in Section 7.4.3 of the standard [16] are also marked)

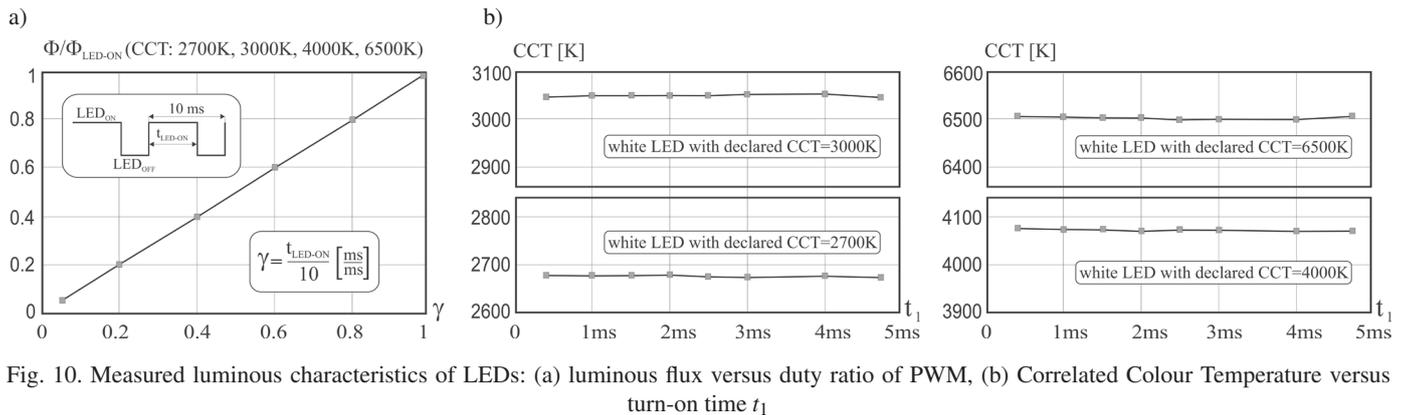


Fig. 10. Measured luminous characteristics of LEDs: (a) luminous flux versus duty ratio of PWM, (b) Correlated Colour Temperature versus turn-on time t_1

staircases, cellars, storerooms, warehouses, external property areas, traffic control, road-signs and billboards, emission of light used as an agent in chemical or biological processes (e.g. in horticulture) and others.

It should be noticed that considerable flicker may also occur in LED lamps which are supposed to be almost flicker-free. This is likely especially in budget lamps supplied according to Fig. 1a. When the electrolytic capacitor dries up due to its operation at an elevated temperature, the greatly increased ripple of the rectified line voltage results in increasing the flicker of the lamp and the user may often not realize this fact.

The search for methods of reducing flicker in LED lamps powered from the AC supply is one of the most important issues in the development of this type of lighting. Such methods are based, in particular, on using additional PFC stages in switched-mode AC/DC converters or the so called valley-fill circuits, in which lower-value non-electrolytic capacitors can be used [4].

A question may arise whether pulse supply of LEDs also causes effects other than flicker. Thanks to fast response of LEDs they can be used, for example, for Visible Light Communication (VLC) with the frequency of light intensity modulation reaching a few megahertz with white diodes whose operation is based on the conversion of blue light through luminophore or tens of megahertz for monochromatic LEDs [18]. To control the luminous flux generated by LED modules for the purpose of dimming in lighting applications Pulse Width Modulation (PWM) is often used. However, to minimize the effects associated with flicker, the PWM frequency is usually much greater than the frequency 100 Hz considered here. Fig. 10 presents the results of measurements showing how the Correlated Colour Temperature (CCT) of LEDs is dependent on the turn-on time t_1 with pulse excitation. Several LEDs were examined with nominal CCT equal to 2700 K, 3000 K, 4000 K and 6500 K. The figure also shows how the luminous flux is dependent on the duty ratio of the 100 Hz PWM waveform. It has been found that comparing to the situation when the diodes are fed with a constant current $I_F = I_{CS}$ the change ΔCCT (measured with the spectroscope BLUE-Wave UVNb-25) for all diodes is within ± 10 K, which is a change indiscernible for a human eye. According to expectations, the measurements have also confirmed a linear relationship between the luminous flux and the PWM

duty ratio γ . To explain the difference between the nominal and actual values of CCT, seen in the figure, we must notice that manufacturers of LEDs declare the CCT category as a specified area on the CIE1931 colour space chromacity diagram. The spread of chromatic parameters of the offered LED series is narrowed only by precise grouping, called binning. All measured values of CCT were included within the ranges guaranteed by the manufacturer in the datasheets.

7. Experimental waveforms

Fig. 11 shows a simplified circuit diagram of an example lamp with two strings of LEDs (overvoltage protection components are not shown). The adjustment of the moments t_1 and t_2 is realized by choosing proper lengths of the strings LED1 and LED2 (the corresponding conduction voltages are given in Table 1). According to the authors, the choice of $t_1 = 2.26$ ms (maximum power for a given current regulator I_{CS}) offers a good trade-off

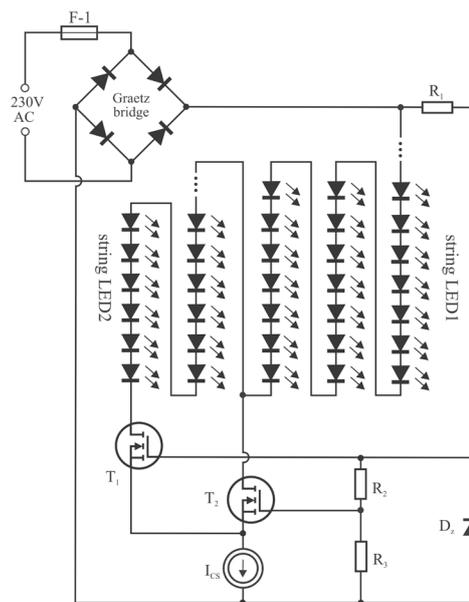


Fig. 11. Simplified circuit diagram of an example lamp with two strings of LEDs

between the acceptable efficiency of the supply system (about 89%) and the margin necessary to comply with formal requirements specified in Section 7.4.3 of the standard EN IEC 61000-3-2:2019.

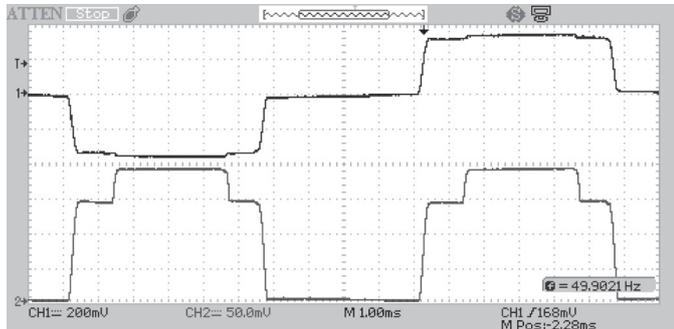


Fig. 12. Waveforms of the line (supply) current drawn by an LED lamp (Channel 1) and its luminous flux (Channel 2)

Fig. 12 presents oscilloscope traces of the line current drawn by the lamp from Fig. 11 (as voltage across a series 4.7 Ω resistor) and the luminous flux produced by this lamp (as voltage generated by a photodiode loaded with a 100 Ω resistor).

8. Summary

LED lamps which are the most readily available on the market, are usually simple and cheap units with a diode rectifier, electrolytic capacitor, series current regulator and a single string of diodes, as shown in Fig. 4a. They are often designed on the basis of application notes of popular IC current regulators, e.g. SM2082 and SR5131, which are dedicated for such applications. More sophisticated solutions of LED lamps, including several strings of diodes, which are switched over in a proper sequence by an IC driver specifically designed for that purpose and patented, whose representative is e.g. CL8800, able to drive six LED strings, may offer better performance but they are usually much more expensive. In authors' opinion, the descriptions, formulas and plots presented in this paper may turn out useful for choosing the proper number of LEDs in a single- or double-string lamp in order to guarantee satisfactory values of the power factor and efficiency, especially as application notes and datasheets of ICs dedicated for such a purpose (current regulators and special drivers) do not provide such detailed information.

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