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LED lighting systems for special applications with a wide range of supply voltages

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Abstract. The relevance of developing integrated lighting systems in conditions of unstable power supply via general-purpose networks is beyond doubt. This article discusses original technical solutions for LED modules that ensure system operation within a wide range of input supply voltages for direct and alternating currents. The effectiveness of the proposed circuit approach is demonstrated using the example of a developed LED lighting device with an electronic LED power system with a driver built using the concept of flyback topology, capable of working with input voltages of both direct (20…300 V) and alternating (36…300 V) currents. The results of experimental studies of electro-optical parameters and characteristics of the manufactured prototypes of the developed lighting systems are presented. It has been shown that the LED modules demonstrate a stable luminous flux and a high luminous efficiency (more than 150 lm/W) at various values and types of supply voltage. The developed lighting systems can be effectively used in domestic and industrial environments, including special-purpose facilities, namely, shelters and warehouses for various purposes, *etc*.

Keywords: LED lighting systems, unstable power supply, flyback topology, high luminous efficiency.

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1. Introduction

One of the challenges of modern energy-efficient technologies is combating global warming and humanity’s growing energy consumption. Today, in Ukraine, the disruption of the centralized power supply creates significant difficulties for people’s everyday lives and leads to significant economic losses, which makes finding ways to ensure stable lighting of critical facilities an urgent and important task. Providing lighting for domestic and industrial facilities, including ones for special-purpose and critical infrastructure, is important for human labor and recreation, as well as creating a favorable light environment improves a person’s psychophysical state [1, 2]. Lighting systems with adjustable spectral composition [3] significantly impact many aspects of human physiology and behavior, including circadian rhythms, sleep, and alertness [4].

One of the ways to create uninterrupted lighting in conditions of unstable power consumption from the general power grid is to get energy from renewable sources or modern batteries. Such systems often combine electric power supply from the general grid with the supply from backup sources [5, 6]. Systems with similar functionality available today usually have low energy efficiency, particularly due to losses at several stages of voltage conversion. It makes the development of new efficient lighting systems capable of using a wide range of supply voltages important.

Modern LEDs open the way for designing highly efficient LED lighting systems by optimizing their parameters and characteristics specifically for targeted applications in various areas of human life, namely: domestic sector [7, 8], industry [9, 10], agriculture [11, 12], *etc*. Moreover, new materials created for the production of white LEDs are often used in other areas, namely, radiation sensors [13, 14], and silicon photomultipliers [15].

The design of a LED lighting device consists of two functionally independent units, namely: a LED cluster and electronic control system. Their interrelation must be strictly coordinated and optimized at various levels of system integration. The LED cluster consists of LEDs (usually with low voltage supply) combined into a LED module with thermal contact to the elements of the cooling system. Cooling systems must ensure that the operating temperature conditions of LEDs and sometimes the power components of electronic control circuits are under optimal operating conditions specified by the manufacturer. Additionally, LED clusters may include optical systems (lenses or other light-shaping elements) with parameters optimized for targeted applications. As an example, for special-purpose lighting devices (illumination of shelter objects, bomb shelters, *etc*.), it is advisable to use diffusers to form the distribution of light fluxes, which reduces the glare effect.

This work aims to develop advanced low-power LED lighting systems for special purposes performing under a wide range of supply voltages, including the development of optimal combinations of LED drivers and LED modules.

2. LED drivers with a wide range of output supply voltages

Modern driver circuit solutions are designed to provide stable operating currents of LEDs in a certain range of control voltages for reliable and stable operation of lighting systems [16]. LED drivers should include protection elements against overvoltage, overload, and short circuits, being highly energy efficient [17]. Their design usually provides the ability to vary the output current over a certain range, allowing one driver design to be used for multiple types of lighting fixtures [18].

In this paper, we will consider the requirements for electronic control systems (drivers) of LED lighting systems, necessary for their operation within a wide range of supply voltages (from 24 to 300 V). This will ensure they are powered both from a centralized AC network and from batteries with a voltage of 24 V and more or from renewable energy sources. Typically, high-performance drivers are built on topologies that provide only an increase or decrease in the control voltage levels additionally to stabilizing the current through LEDs. Given the selected input voltage range of the LED systems, it was decided to use a driver topology that reduces the output control voltage to a level that matches the control voltage range of the LED modules, which is efficient and safe.

To realize this concept of driver design, we used a circuit based on a flyback topology [19] due to its numerous advantages (small number of components, low cost, compact size, ability to operate in a wide range of input voltages with high stability of the output voltage or current). A block diagram with the main components of the developed LED driver is shown in Fig. 1. The chosen topology involves using the pulse width modulation (PWM) to control the clocking transistor TR2, which enables the conversion of voltage levels using a power choke. The flyback topology reduces the complexity and cost of the driver while providing the required functionality. However, its disadvantages include a high current through the clocking transistor and relatively large choke dimensions.

The driver circuit uses a passive filter based on capacitors and a choke to reduce electromagnetic interference (Block 1). This filter suppresses the fundamental frequency of the PWM converter and its harmonics. To ensure that the driver operates with both AC and DC voltages, the diode bridge VD1 (Block 2) is used to rectify the input voltage, and the filter capacitor C4 stabilizes the rectified voltage.

To implement the PWM (Block 3), the HV9910 chip [20] was chosen. The selected chip is equipped with a built-in voltage regulator that ensures its stable power supply. In addition, the HV9910 chip allows changing the output current using an analogue and digital signal. The on-chip clocking transistor driver provides efficient control of the transistor without the need for additional components, and the ability to limit the maximum output current of the driver increasing reliability.

Although the typical use of the HV9910 chip involves building a galvanically coupled LED driver, a galvanically uncoupled driver was developed due to the ability to change the output current using an analogue signal (0…250 mV). This allowed the additional decoupling between the input and output circuits, increasing safety and flexibility in application (Block 4).

After rectification, the voltage is applied to the inductor (Block 4), through which current flows and energy is stored when the transistor opens. The output current value is controlled by the HV9910 PWM controller

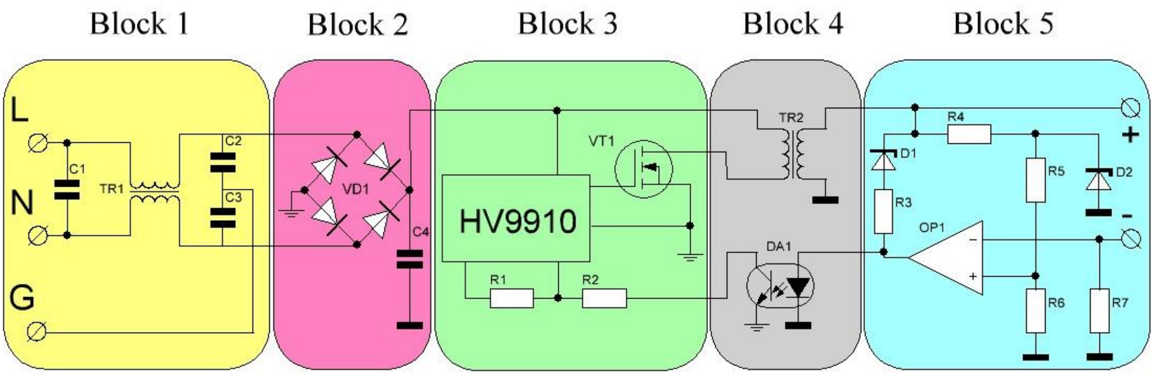

Fig. 1. Block diagram of the developed LED driver with a wide input voltage range.

using the current-setting resistor R1, which determines the maximum power of the driver at a constant input voltage. Changing the analogue input of the controller as input of the reference voltage of the comparator (with which the voltage on the current-setting resistor is compared) allows the changing of the maximum current of the transistor. The developed driver implements output voltage feedback (Block 5). To do that a typical solution based on the Zener diode D1 is used. When the driver output voltage exceeds a certain threshold value (set by Zener diode D1, in this case 27 V), D1 goes into the "breakdown" mode, the optotransistor DA1 of the opto-coupler opens, initiating a decrease in voltage at the input of the HV9910 comparator. This reduces the turn-on time of the clock transistor and, accordingly, reduces the output voltage.

To stabilize the output current, the driver implements feedback based on an operational amplifier and current-setting resistors. The inverted input of the operational amplifier is supplied with a reference voltage formed by the Zener diode D2 and a resistor divider, and the direct input is supplied with the voltage from the current-setting resistor R6. When the voltage across the operational amplifier resistor drops, a voltage sufficient to trigger the optocoupler is generated at its output, which leads to the opening of the optotransistor DA1 and, as a result, to a reduction in the opening time of the clocking transistor.

A photo of the experimental prototype of the developed LED driver with a wide range of input supply voltage is shown in Fig. 2. The use of various current-setting resistors, Zener diodes, and inductors in the developed driver allows the creating of LED lighting devices with a current supply of LED up to 1 A and a control voltage up to 24 V.

3. LED modules with high luminous efficiency

In the proposed design of the lighting system, white Samsung LM301H LEDs [21] with a luminous efficiency close to 200 lm/W and a maximum electrical power close to 0.6 W were used to create light clusters combined into a LED module. Fig. 3 and Table 1 show the experimentally measured spectrum and parameters of the LM301H LEDs. To determine the spectral and energy parameters of LEDs, we used a complex for measuring the electro-optical parameters of LEDs based on a spectro-radiometer NAAS-2000, an integrating sphere with the diameter 0.3 m, and a DC power supply WY-3010 manufactured by Everfine (China).

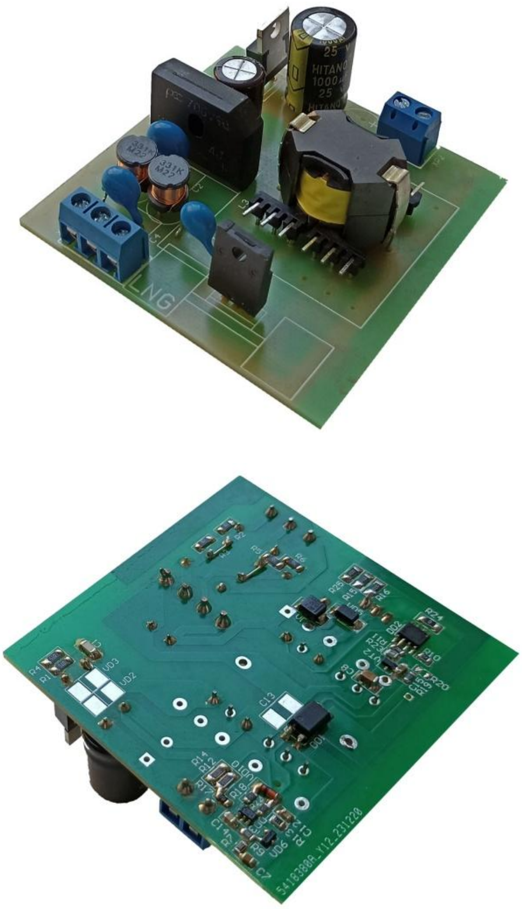

Fig. 2. Photo of the experimental prototype of the LED driver with a wide range of input supply voltages.

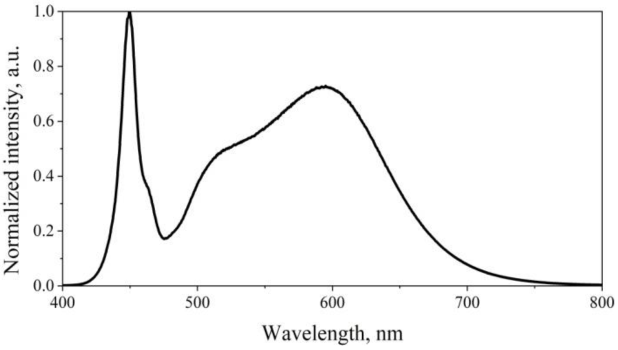

Fig. 3. Typical emission spectrum of Samsung LM301H LED. The emission intensity is normalized to the maximum value.

Table 1. Electro-optical parameters of Samsung LM301H LED.

I, mA	U, V	P_e, W	L, lm	CRI	P_r, W	P_q, W	η	η_{eff}
65	2.766	0.180	37.5	82.7	0.112	0.068	0.622	208
100	2.839	0.284	56.5	82.9	0.169	0.115	0.594	199
200	3.080	0.616	113	83.1	0.348	0.268	0.565	183

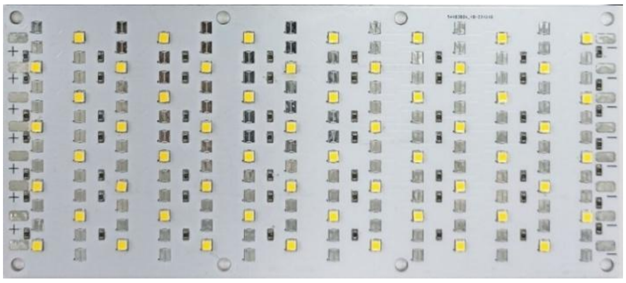

Fig. 4. Experimental prototype of a LED module with mounted Samsung LM301H LEDs.

In any energy conversion system, some energy will be wasted on side effects. Therefore, we considered that only part of the electrical energy supplied to the LED is converted into light radiation, and the rest into heat. Hence, when designing lighting systems, it is important to ensure reliable cooling of LEDs.

The developed LED module consists of a printed circuit board made of 1.5 mm thick copper/aluminium foil with LEDs mounted with maximum distribution over the area for better heat dissipation generated during their operation (Fig. 4).

The use of foiled aluminium allows efficient heat dissipation from the LEDs, which prevents them from overheating. To cool LED light sources, cooling systems based on various operating principles are used: passive radiators [22], thermoelectric coolers [23], piezoelectric fans [24], and jet coolers [25]. When designing high-power LED lighting systems, two-phase heat transfer devices (heat pipes [26], thermosyphons [27], steam chambers [28], *etc.*) are often used, but passive cooling systems [29, 30] based on radiators made of homogeneous materials with high thermal conductivity have the longest service life. A great advantage of these systems is the possibility of reusing cooling systems after the lighting systems as a whole become obsolete.

Passive radiators are particularly common in low-power lighting systems and can be manufactured as a specially shaped radiator profile and as a specialized radiator that is also the body of the lighting device (radiator housing), which makes such a device more compact.

4. Results of experimental studies of a special-purpose LED lighting system

The developed LED cluster was mounted (with thermal contact) on the radiator housing of a serial lighting device DBB37U (VATRA) (Fig. 5) to replace obsolete Seoul Semiconductor LEDs produced in 2012. The LED modules were attached to the radiator housing using threaded connections, and reliable thermal contact between the LED module and the radiator housing was ensured using heat-conducting paste. A special feature of this radiator housing is that it also allows the placement of a specially developed LED driver in its design. This modernization made it possible to reuse the elements of the lighting fixtures (radiator housing, diffuser, housing elements) and reduce the environmental impact of their disposal. At the same time, the new lighting device has characteristics that meet modern requirements for LED lighting devices.

Fig. 5. Experimental prototype of a LED lighting system with a wide range of input supply voltages.

The light and spectral parameters were determined using modern metrological equipment: a matrix spectroradiometer from Instrument system CAS-140 and an integrating sphere with a diameter of 2 m, which allowed real-time monitoring of the light and spectral parameters of the lighting device.

For power supply and determination of the electrical parameters of the LED lighting fixture, HAMEG HMP4040 and Delta D400-04-01C DC power supplies and Everfine T500 AC power supplies were used. During the experiments, the values of the electro-optical parameters of the lighting device were measured, from the moment of switching on to the moment of temperature, power, light, and spectral parameters stabilization.

Fig. 6 shows the change in luminous flux and luminous efficiency when the lighting device is powered by a constant voltage within the range 20…300 V with the following increments: 4 V within the range 20…36 V, 12 V within the range 36…120 V, and 20 V within the range 120…300 V.

One can see that the highest luminous efficiency (close to 173 lm/W) and stable luminous flux close to 1884 lm) are achieved within the input voltage range 120…220 V. At low input voltages (up to 50 V), there is a decrease in light output and efficiency, which indicates a lower efficiency of the driver. At high voltages (over 220 V), the efficiency and lumen output also slightly decrease.

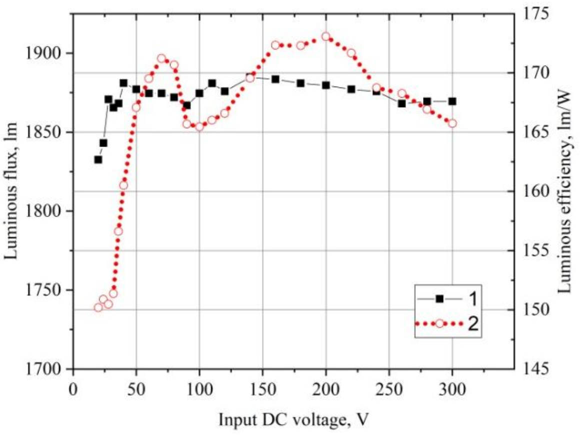

Fig. 6. Changes in the luminous flux value (*1*) and luminous efficiency (*2*) when the lighting system is powered by a constant voltage.

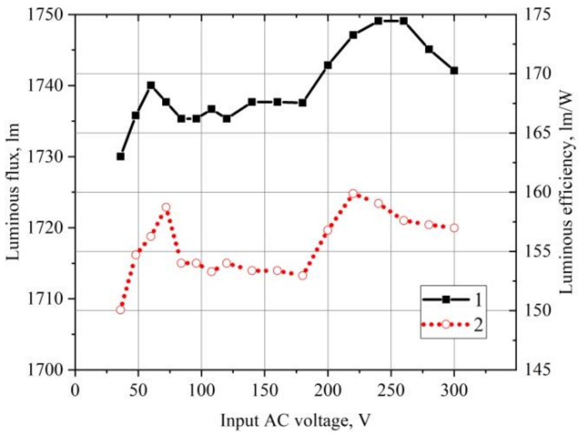

Fig. 7. Changes in the value of luminous flux (*1*) and luminous efficiency (*2*) when the lighting system is powered by an alternating voltage.

The test results of the lighting system, when powered by AC voltage sources within 36… 240 V (50 Hz), are shown in Fig. 7. Within the range 36…120 V, measurements were made with 12 V increments, and within the range120…250 V with 40 V increments.

The dependences shown in Fig. 7 display that the luminous flux remains relatively stable at different values of the input AC voltage, ranging from 1730 to 1749 lm. The luminous efficiency is more variable, decreasing to a minimum close to 150 lm/W at 36 V, but reaching a maximum close to 175 lm/W at 240 V. This indicates the stability of the luminous flux within a wide voltage range.

The change in power and luminous efficiency values under different power supply conditions is caused primarily by a change in the operating modes of the HV9910 LED driver chip, which affects the transient processes in the driver operation. At the same time, Figs. 6 and 7 show that the luminous flux of the lighting system when operating from DC or AC deviates for no more than 3% of its average value within the entire range of supply voltages, which meets the requirements for lighting devices of this type. When operating within the entire tested range of power supply voltages for DC and AC sources, the driver efficiency is at least 150 lm/W, which is sufficient for lighting systems of this type.

5. Conclusions

Studies of the developed lighting systems have shown the possibility of using a wide range of power sources for their operation, both direct current (with a voltage within 20…300 V) and alternating current (36…300 V, 50 Hz).

The developed driver ensures stabilization of the LED luminous flux within a wide range of supply voltages. When powered by a constant voltage, the highest luminous efficiency of the developed lighting system (close to 173 lm/W) and a stable luminous flux (close to 1884 lm) are achieved within the input voltage range 120…220 V. At low input voltages (up to 50 V), there is a decrease in light output and efficiency, indicating a lower efficiency of the driver. At high voltages (over 220 V), the efficiency and lumen output also slightly decrease.

When supplying the lighting system with an alternating voltage, the highest luminous efficiency (close to 175 lm/W) is achieved at a voltage close to 240 V. The luminous flux is stabilized at about 1740 lm, with slight fluctuations within the range 60…200 V. At low voltage values (up to 60 V), the luminous flux and efficiency show fluctuations. At high voltage levels (above 250 V), the efficiency and luminous flux decrease slightly, indicating potential problems with heat dissipation or other factors affecting the stability of the LED device.

The created lighting system provides a luminous efficiency of more than 150 lm/W and deviations of the output luminous flux from the average value of no more than 3% within the entire range of supply voltages, which meets the requirements for lighting devices of this type.

The developed lighting systems can efficiently use a common power supply network and provide reliable lighting in its absence using exclusively low-voltage DC sources not using voltage level and type conversion systems.

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Kornaga V.I.: conceptualization, formal analysis, investigation, validation, writing – original draft.
Pekur D.V.: formal analysis, investigation, data curation, visualization, writing – original draft.
Kolomzarov Yu.V.: investigation, data curation, visualization.
Chernenko V.V.: formal analysis, writing – review & editing.
Korkishko R.M.: validation, investigation, writing – review & editing.
Dvernikov B.F.: validation, investigation.
Snopok B.A.: conceptualization, validation, writing – review & editing.
Sorokin V.M.: conceptualization, methodology, formal analysis, supervision, writing – review & editing.

Світлодіодні системи освітлення спеціального призначення з широким діапазоном напруг електроживлення

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Анотація. Актуальність розробки інтегрованих систем освітлення в умовах нестабільного електропостачання мережами загального призначення не викликає сумнівів. У статті розглядаються оригінальні технічні рішення світлодіодних модулів, які забезпечують роботу системи в широкому діапазоні вхідних напруг живлення як постійного, так і змінного струму. Ефективність запропонованого схемотехнічного підходу продемонстровано на прикладі розробленого світлодіодного освітлювального приладу з електронною системою живлення світлодіодів, драйвер якого побудовано за зворотноходовою топологією, здатного працювати з вхідними напругами як постійного (від 20 до 300 В), так і змінного (від 36 до 300 В) струмів. Наведено результати експериментальних досліджень електрооптичних параметрів і характеристик виготовлених прототипів розроблених освітлювальних систем. Показано, що світлодіодні модулі демонструють стабільний світловий потік і високу світлову віддачу (понад 150 лм/Вт) при різних значеннях і типах напруги живлення. Розроблені системи освітлення можуть бути ефективно використані як у побутових, так і в промислових умовах, у тому числі на об'єктах спеціального призначення, таких як укриття, склади різного призначення тощо.

Ключові слова: світлодіодні системи освітлення, нестабільне живлення, зворотноходова топологія, висока світлова віддача.