Semiconductor Physics, Quantum Electronics & Optoelectronics, 2024. V. 27, No 2. P. 242-249.

Optoelectronics and optoelectronic devices

Design of powerful high-performance drivers for special-purpose LED lighting systems

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Abstract. This paper presents the results of the study of the parameters and characteristics of the developed high-performance electronic control circuits for special-purpose LED lighting systems based on a two-stage forward converter (driver) with an output power of more than 200 W. Operation of the developed driver in the output power range of 13 to 202 W and the supply voltage range of 160 to 250 V was investigated. The maximum efficiency of the developed power supply system at the voltage of 240 V and the output power of 140 W is 89.9%. For the chosen topology, further voltage increase may increase the efficiency, but lead to accelerated degradation of the driver components. The results of the experimental studies of the developed drivers showed the drivers efficiency in the range of 84 to 90% at a load of 52…202 W with a power factor above 0.97 and a nonlinear current distortion factor less than 23.4% over the entire studied range of supply voltages. The high efficiency of the developed driver in a wide range of output power suggests the possibility of using the driver in lighting systems that provide additional power supply to energy storage systems (batteries), including those ensuring operation in the absence of mains power supply.

Keywords: LED driver, power factor, forward converter, efficiency, LED lighting systems.

https://doi.org/10.15407/spqeo27.02.242
PACS 42.72.-g, 85.60.Jb, 92.60.Pw

Manuscript received 03.04.24; revised version received 27.05.24; accepted for publication 19.06.24; published online 21.06.24.

Introduction

Electronic power supply systems (drivers) are an important component of LED lighting devices. Creation of lighting systems with combined power supplies, *i.e.* when other power sources are used in addition to the general power supply network (batteries [1], solar photovoltaic modules [2, 3], wind turbines [4, 5], *etc.*), requires creation of drivers capable of providing high efficiency in a wide power range. Such systems are often based on a single-mains power supply, which is used both to supply power to LEDs and to charge batteries or other devices (laptops, USB gadgets, *etc.*).

Today, LED lighting systems are increasingly replacing the ones based on other types of radiation sources [6]. LED lightning systems can have a power of 200 W or more [7, 8] (in particular, by using two-phase heat transfer devices – heat pipes [9] for cooling). Their power supply systems are characterized by a long service life, high efficiency at high power factor (PF) values [10], and low nonlinear current distortion coefficient (Total Harmonic Current Distortion, THDi) [11]. At the same time, the power of special-application lighting systems (lighting of shelters or underground storage facilities, *etc.*) is usually up to 50 W. When constructing lighting systems with a possibility of using a backup power supply (from the general power supply network and from electricity storage systems), the power of the supply system should exceed the power of the lighting system by 4-5 times to ensure operation of electricity storage systems (batteries). Such power redundancy makes possible functioning of special-purpose lighting systems even in the absence of power supply for approximately 80% of the total time.

Use of modern materials (molybdenum disulfide [12], graphene [13], carbon nanotubes [14], macroporous silicon [15–17], *etc.*) to create semiconductor structures further contributes to an increase in the power and decrease in the cost of semiconductor components, which significantly expands their application. Development of a modern gallium nitride element base for creating high-frequency transistors (GaN transistors [18, 19]) and the latest effective methods of their thermal regulation [20, 21] allow the development of new radar systems, the use of which is continuously expanding. Widespread implementation of GaN transistors has made them available for creating compact and energy-efficient power supply systems for LED lighting systems, in particular, with adjustable spectrum [22], as well as other modern electronic devices.

However, the most widespread LED drivers today are those using silicon power switches that are usually based on forward [23, 24], reverse [25, 26], resonant [27, 28] or quasi-resonant [29, 30] topologies. The most common driver design for high-power LED lighting systems has the forward-pass topology type. The direct-path topology has a number of advantages such as electrical decoupling of input and output circuits, simple design and low cost of electronic components, and the ability to integrate elements into the electronic circuit to ensure high power factor and high efficiency over a wide range of operation powers. The modern component base of silicon microelectronics allows the development and manufacture of highly efficient drivers with a direct-pass topology operating at frequencies of 16….200 kHz.

Use of a high conversion frequency makes it possible to significantly reduce the driver weight and dimensions (especially in terms of optimizing the size of inductive components) as well as to expand the driver functionality while maintaining high efficiency.

Modern LED lighting system drivers must provide stable LED currents regardless of voltage fluctuations in the mains. At the same time, important requirements for such systems are absence of electrical interference and high power factor [31]. The latter is especially difficult to implement in the systems with possible changes of the output power over a wide range.

The aim of this work is to develop powerful drivers based on a direct-path topology for creating special-purpose LED lighting systems that would provide the possibility of combined power supply from the general power supply network and energy storage devices (batteries). The paper studies the operational parameters and characteristics of the developed drivers in different modes taking into account the operation conditions.

2. Design of forward-acting LED driver and its features

When designing the structures of LED lighting systems for special purposes, the electrical safety of such devices should be taken into account. For this purpose, it is desirable to use low LED supply voltages (up to 40 V), which, in addition to safety, increases the overall reliability of the lighting system (high voltages applied to LEDs connected in series can lead to failure of individual LEDs). In this case, it is especially important to use galvanic isolation of the LED current-carrying parts from the general power supply network [32]. According to these requirements, electronic control circuits are divided into galvanically isolated and galvanically non-isolated. Galvanically isolated control circuits are used in lighting devices where no direct contact of a human with metallic (or non-metallic electrically conductive) parts of the lighting systems is ensured. Galvanically isolated electronic control circuits have a much wider range of applications due to their safety, but the feasibility of their use must be justified, as their cost is higher than that of galvanically non-isolated ones. At present, in most cases, galvanically uncoupled systems are practically out of use due to the higher safety of galvanically coupled circuits.

An important electrical parameter of all electronic control circuits that needs to be ensured is the high-power factor [33, 34]. Today, there are two types of electronic control circuits that provide an increased power factor (passive and active power factor corrector). The main advantage of electronic control circuits with a passive power factor corrector is their simplicity of implementation. At this, the power factor that can be achieved does not exceed 0.85, which is insufficient for industrial applications. Power factor correctors are mainly used for low- (up to 10 W) and medium-power (up to 50 W) lighting systems. An electronic control circuit with an active power factor corrector is more advanced, allowing for a power factor of up to 0.99. The current waveform of a power supply at the input of the electronic control circuit without a power factor corrector does not match the input voltage waveform, which causes emission of current harmonics into the power supply network. The situation somewhat improves when a passive power factor corrector is used. However, the input voltage waveform is best matched to the input current in electronic control circuits with an active power factor corrector, which ensures a high power factor. In order to develop a safe and energy-efficient driver, a two-stage electronic control circuit with an active power factor corrector and a voltage- and current-stabilized switching converter was used in this study. The block diagram of the developed driver is shown in Fig. 1.

The developed electronic control circuit is based on a forward half-bridge converter using a TL494 PWM controller. This controller uses external clocking transistors as separate components, which allows for efficient heat dissipation during operation and implementation of an electronic control circuit with the power of more than 200 W. Since the half-bridge topology is used, which provides an alternate switching on of each of the clocking transistors, it is not allowed to open the transistors simultaneously, as this will lead to a decrease in efficiency or failure of the driver.

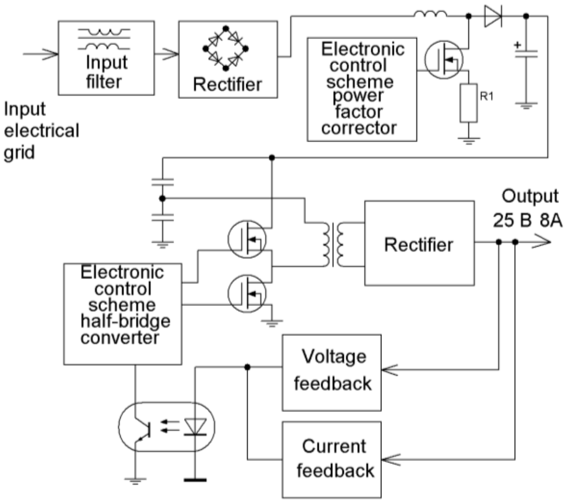

Fig. 1. Block diagram of a galvanically isolated decoupled driver with an active power factor corrector.

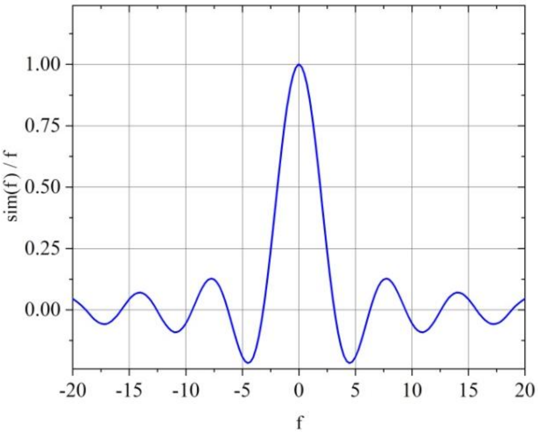

Fig. 2. Spectrum of rectangular periodic pulses.

The selected TL494 controller does not allow simultaneous opening of the clocking transistors, and also provides additional "dead time" between openings to complete transients that occur due to the parasitic inductance and capacitance of the transistor gate. The dead time between closing one transistor and opening the other transistor further increases the reliability of the driver.

When the driver operates, the clocking transistor operates in saturation mode (full opening and closing). Hence, the shape of one clocking pulse is a rectangle or close to it. This leads to appearance of high-frequency harmonics, because Fourier transform of a rectangular pulse gives the value of harmonics sin$x$/x, see Fig. 2. To prevent high-frequency harmonics from entering the network, a passive filter optimized for this driver design, which consists of an adjacent choke with counter-connected windings and filter capacitors, is installed at the input of the developed electronic circuit.

Since the developed driver is designed to power LEDs and its power exceeds 200 W, minimal output current ripple and high power factor must be ensured. Only two-stage electronic conversion circuits are suitable for this purpose. That is why the developed circuit has an active power factor corrector based on a L6561 chip after the diode bridge, which allows for compliance with the electrical parameters in accordance with the DSTU IEC61000-3-2:2004. Another advantage of using an active power factor corrector is a constant voltage of 400 V at the driver input. Therefore, at the correct design of the driver transformer, the rated voltage at the driver output will remain constant (in the absence of current limitation) at fluctuations of the input mains voltage.

The TL494 controller PWM generation frequency in the range of 10 to 150 kHz can be set using an external resistor and capacitor. In our case, the optimal frequency is 30 kHz. Such value enables minimizing the energy losses due to switching by clock transistors and rectifier diodes.

To limit the maximum values of the driver voltage and current, a feedback loop based on a two-channel operational amplifier TSM103W is implemented. A characteristic feature of this operational amplifier is the presence of a built-in voltage regulator, which allows the use of only one chip to implement both current and voltage feedback.

3. Hardware prototype and experimental results

Based on the developed electronic circuit, an experimental sample of the driver was manufactured. Fig. 3 shows a three-dimensional model of the electronic control circuit visualized in the Altium Designer software.

An experimental sample of the electronic control circuit of the driver is shown in Fig. 4. In addition to the terminal for connecting 220 V supply voltage and the output for connecting a load, it also has a stabilized 5 V output, which may be used to supply a wide range of devices operating at this voltage.

To determine the performance characteristics of the driver, it was experimentally studied using the following equipment: Tektronix DMM4050 precision digital multimeters, TPS 500V AC power supply, PF9811 power meter, and Agilent 6812B AC power supply. An electronic load with a maximum power of 300 W was used to study the driver operation in different modes.

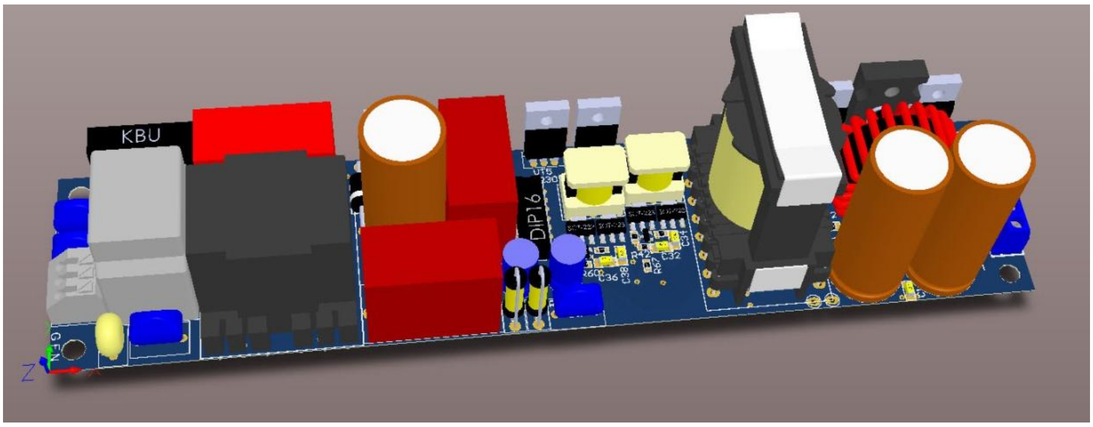

Fig. 3. Three-dimensional model of the electronic control circuit.

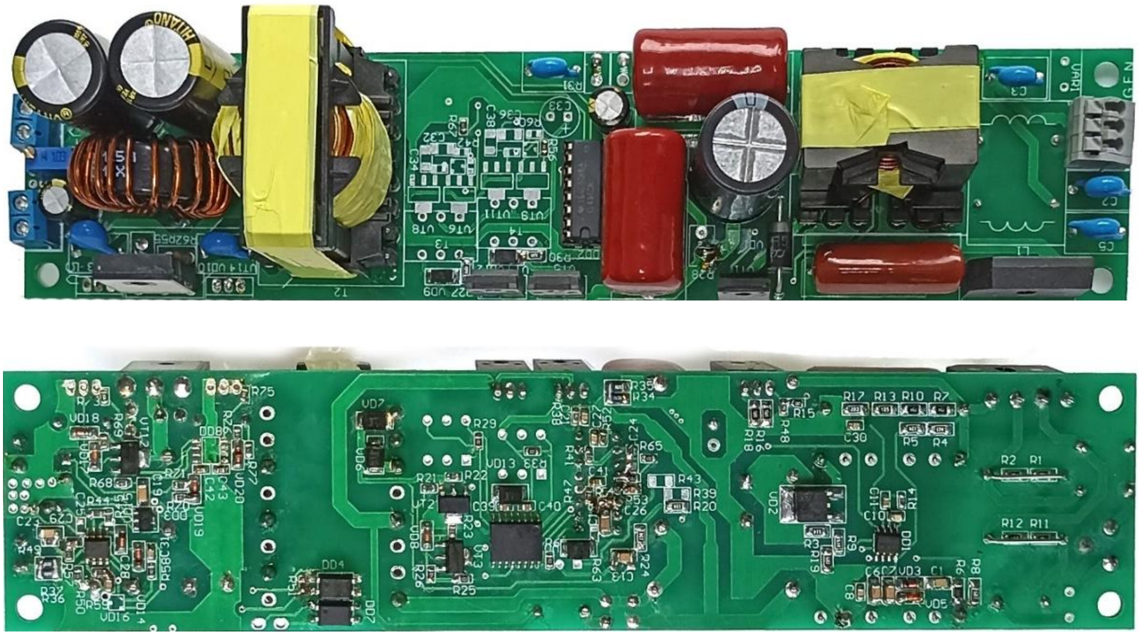

Fig. 4. Experimental sample of the developed electronic circuit for controlling the primary converter.

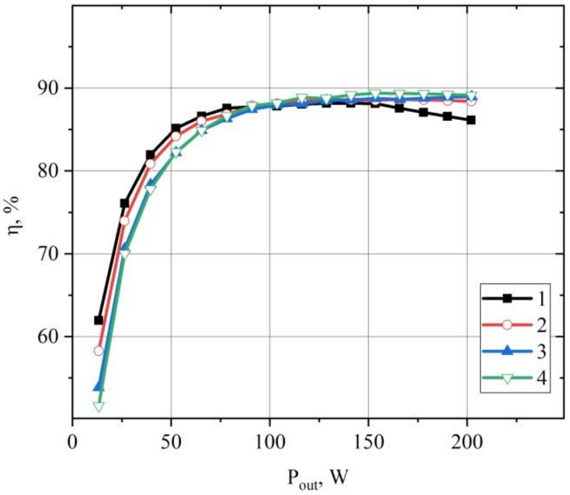

Fig. 5. Dependence of driver efficiency (η) on output power (*P*) at different input supply voltages: 160 (*1*), 190 (*2*), 220 (*3*), and 250 (*4*) V.

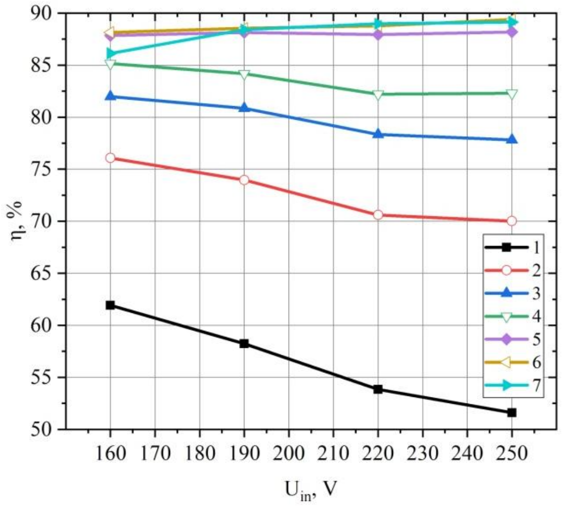

Fig. 6. Dependence of driver efficiency (η) on input supply voltages (U_{in}) at different output powers: 13 (*1*), 26 (*2*), 39 (*3*), 52 (*4*), 104 (5), 153 (*6*), and 202 (*7*) W.

The efficiency (η) of converting the AC mains voltage to DC voltage by the driver, defined as the ratio of the output power to the input power, was investigated for the supply voltages of 160, 190, 220, and 250 V, as shown in Figs. 5 and 6.

Increasing the load power from 13 to 75 W leads to a gradual increase in the efficiency from 52% to 84%. With a further increase in the output power, the efficiency remains in the range of 84–90%, followed by a decline when the output power exceeds 150 W. Thus, the developed driver can provide the conversion efficiency in the range of 84–90% at the output power in the range of 52 to 202 W.

Dynamics of the efficiency change with the input supply voltage shows that the minimum efficiency value is 52.1% at the supply voltage 250 V and the maximum is 89.9% at the voltage 240 V. Such fluctuations in the driver efficiency may be explained by a change in its operation mode, namely, a change in the conversion frequency and the value of current through the clock transistor. An increase in the conversion frequency leads to an increase in switching losses, since each of the transistors and diodes has parasitic capacitances.

Given that the developed driver has high power, it is important to ensure a high power factor and low current harmonic distortion in all the studied operation modes.

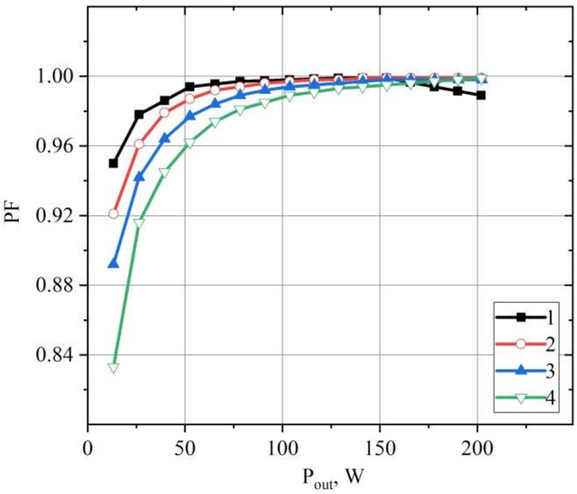

Fig. 7. Dependence of power factor (PF) of the driver on the change of output load at different input supply voltages: 160 (*1*), 190 (*2*), 220 (*3*), and 250 (*4*) V.

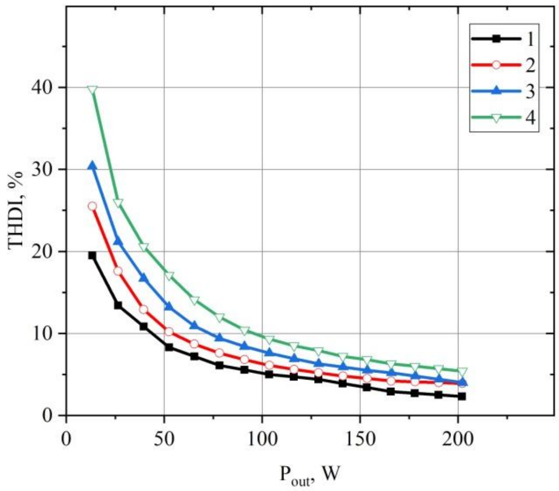

Fig. 8. Dependence of nonlinear current distortion factor (THDi) of the driver on the change of output load at different input supply voltages: 160 (*1*), 190 (*2*), 220 (*3*), and 250 (*4*) V.

Fig. 7 shows the dependence of the power factor on the output power value. It can be seen from this figure that at the power of more than 50 W, the power factor exceeds 0.94 and only slightly decreases with an increase in the power over 150 W due to the use of the developed active power factor corrector.

Fig. 8 show that the nonlinear current distortion factor values are within the acceptable limits (up to 10%) for the powers above 100 W for all the supply voltages. This indicates that the total harmonic distortion levels remain within the permissible limits over the entire output power range. In general, the obtained results demonstrate the effectiveness of the system to maintain the THDi at a low level.

Low THDi is important to ensure the quality and reliability of the power supply system, as high levels of harmonic distortion can lead to overheating and equipment failure. Keeping THDi low is particularly important at high power levels. Overall, the results presented in Fig. 8 demonstrate the success of the system in managing total harmonic distortion at various power levels and supply voltages.

4. Conclusions

This work developed an efficient driver for special-purpose LED light sources with a power of more than 200 W based on a forward converter that maintains high efficiency across a wide range of operation powers.

The results of the experimental studies of the developed driver showed its efficiency in the range of 84–90% at the load in the range of 50 to 202 W with the power factor above 0.97 and THDi less than 23.4%. The maximum efficiency of the developed power supply system is 89.9% at the voltage of 240 V and the output power of 140 W.

In order to enhance accessibility and feasibility of the design, a cohesive component framework was employed, resulting in cost reduction of the end product and optimization of the manufacturing procedure. Ultimately, use of a unified component base not only benefits the manufacturer in terms of cost and production efficiency, but also provides a more reliable and user-friendly product for consumers.

For power levels above 100 W, the THDi values remain within the acceptable ranges (up to 10%) for all the supply voltages. This observation suggests that the overall harmonic distortion levels are within the acceptable thresholds throughout the entire output power range. Overall, the findings indicate that the driver is successful in maintaining low THDi levels over a wide power range.

The obtained experimental results are promising and pave the way for developing efficient drivers for special-purpose lighting systems.

Acknowledgements

This work was supported by the National Research Foundation of Ukraine (project No 2022.01/0037).

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Pekur D.V.: formal analysis, resources, investigation, validation, writing – review & editing.
Kolomzarov Yu.V.: conceptualization, writing – review & editing.
Minyaylo M.A.: investigation, writing – review & editing.
Sorokin V.M.: conceptualization, funding acquisition, methodology, supervision, project administration.

Розроблення потужних високоефективних драйверів для світлодіодних систем освітлення спеціального призначення

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Анотація. У даній роботі наведено результати дослідження параметрів і характеристик створених високоефективних електронних схем керування світлодіодних систем освітлення спеціального призначення, побудованих на основі двокаскадного прямоходового перетворювача (драйвера) з вихідною потужністю більше 200 Вт. Було досліджено роботу розробленого драйвера в діапазоні вихідних потужностей від 13 до 202 Вт та діапазоні напруг живлення 160…250 В. Максимальна ефективність розробленої системи електроживлення становить 89.9% при напрузі 240 В та вихідній потужності 140 Вт. З урахуванням особливості вибраної топології подальше підвищення напруги може підвищити коефіцієнт корисної дії, проте призвести до пришвидшення деградації компонентів драйвера. Результати експериментальних досліджень розроблених драйверів показали їхню ефективність у діапазоні 84–90% при навантаженні в діапазоні 52…202 Вт з коефіцієнтом потужності вищим за 0.97 та коефіцієнтом нелінійних спотворень струму меншим ніж 23.4% в усьому досліджуваному діапазоні напруг живлення. Висока ефективність розробленого драйвера в широкому діапазоні вихідних потужностей передбачає можливість його використання для побудови систем освітлення, в яких реалізується додаткове забезпечення електроживленням систем накопичення електроенергії (акумуляторних батарей), у тому числі для забезпечення роботи в умовах відсутності мережевого електроживлення.

Ключові слова: світлодіодний драйвер, коефіцієнт потужності, прямоходовий перетворювач, ефективність, світлодіодні системи освітлення.