Optoelectronics and optoelectronic devices

Intelligence system for monitoring and governing the energy efficiency of solar panels to power LED luminaires

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Abstract. Developed in this work are the principles for creation of a system to control and governing the energy efficiency of solar panels providing power supply for LED luminaires. Realization of these principles allows the most efficient using the electric power generated by solar panels, to save in a real-time scale the data about system functions as well as provide a complex analysis of these data. Optimization of using the electric energy generated by solar panels will enable to determine the maximum possible power in each specific moment and to automatically tune its consumption. The complex data obtained with this system can be further used for not only statistical fixation of the produced and consumed electric energy in fact but also for prediction of the energy amount that will be generated by these solar panels in future. The analysis of results will enable to optimize the area of solar panels and more exactly determine parameters of electronic components both for illumination systems and designing solar photoelectric stations of various purposes.

Keywords: photoconverter of solar energy, diagnostics of solar panels, illumination system, supercapacitor.

https://doi.org/10.15407/spqeo24.02.200
PACS 42.72.-g, 52.80.Mg, 85.60.Jb, 92.60.Pw

Manuscript received 17.03.21; revised version received 22.04.21; accepted for publication 02.06.21; published online 16.06.21.

1. Introduction

Lowering the power inputs for illumination can be reached, in particular, by wider application of LED illuminating equipment [1–3]. To construct power LED luminaires as light sources, LED matrices and high-power modules are now used more and more often [4, 5]. These sources are equipped with efficient cooling systems based on two-phase heat-conducting facilities, namely: thermosyphons [6, 7], heat pipes [8–12] and vapor chambers [13].

Providing the set operation temperature regimes for light-emitting crystals by using an efficient heat removal enables to create illumination systems possessing long operation life, and joining the light-emitting crystals into LED matrices enhances reliability as well as manufacturability of producing these devices. Application of energy-efficient LED light sources instead of incandescent lamps enables to lower power consumption more than 10-fold due to the higher luminous efficacy and to additionally reduce electric power consumption by 40–50% owing to the possibility to automatize control of illumination [14].

The further increase in the energy efficiency of power LED luminaires can be provided by powering them from combined systems based on renewable energy sources, for instance, solar panels (SP) [15, 16], which enables to reach additional economy of the energy consumed from the centralized network.

It is especially topical to use solar panels in the case of necessity to continuously illuminate premises in day time, too [17], for example, of sales area in shops, warehouses, workrooms of large area, underground and autopark complexes, tunnels and underground railway stations.

Generation of the electric power in SPs is based on direct transformation of Sun energy into the electric power in semiconductor photoelectric converters – solar elements (SE). This transformation takes place due to the physical phenomenon – photoeffect.

Photoelectric generation takes place when illuminating the SP surface with a flux of solar light quanta (from the spectral range where their absorption is provided, and photoeffect arises in solar elements, from which SPs consist of). It means that the electrical voltage on the SP terminals is generated by solar light quanta (photons) of the energy that exceeds the forbidden gap of semiconductor from which these SE are produced.

The level of illuminance at the surface of photo-electric converters plays a decisive role in operation of illumination systems powered from solar panels in the day time. Generation of the energy by using SPs can be essentially changed in dependence on the season and time of day, temperature, level of energy illuminance, *i.e.*, on weather conditions. Reaching the highest energy efficiency in conditions of unstable illuminance needs choosing the optimal parameters and type of SPs. Since providing operation of LED light sources in these illumination systems directly from solar energy is impossible in conditions of changing the generated power, therefore it is reasonable to develop intelligence systems for controlling and managing, which could be capable to provide efficient using the generated power as well as promising energy accumulators. Usually, power supply systems based on SPs contain in their construction the energy accumulators (accumulator batteries [15, 16, 18]), which enable to accumulate energy under conditions favorable for photogeneration and use it if necessary. At the same time, application of accumulators that, as a rule, have a relatively short operation life, reduces reliability of this system as a whole.

To avoid the above deficiency, the authors of the works [18, 19] offered the concept of designing prospective illumination systems with a combined power supply, when supercapacitors are used as accumulators of energy. The operation life of these capacitors is comparable with other electronic components of such a system. Application of the supercapacitors needs additional investigations to develop the intelligence systems suitable for controlling the LED illumination devices.

Another feature of these power supply systems based on SPs is variability of solar illuminance in dependence on SP orientation relatively to the direction to Sun, which should be taken into account when designing the intelligence governing systems. The main components of solar illumination are as follows: direct, scattered (diffuse) and reflected ones. Relationships between these components are important for defining the constructive decisions when mounting the solar batteries.

In particular, for the territories with domination of the direct component, placement of SPs on the facilities that allow following the Sun has its advantages. These systems can enhance their energy yield by the value up to 20% [20, 21] as compared with the fixed SP position. In the territories with increased cloudness, one can mainly observe scattered and reflected radiation, therefore, the systems that provide following the Sun will not have essential advantages in power generation, and at the same time can increase expenses and complexity but decrease reliability of the system in whole.

When designing the governing systems for illumination devices that use the solar energy, one should take into account some features of solar element operation as well as other factors influencing the energy efficiency at large (correlations between the energy generated by SP, capacity of energy accumulators and power of the LED illumination devices). More reliable determination of parameters characterizing solar generation and system performances is possible due to performing direct experimental investigations under real conditions of exploitation.

The aim of this work is to develop an intelligence governing system for optimization of the energy efficiency inherent to SPs that are used for power supplying the LED illumination facilities. This system will enable to provide more efficient using the electric power generated by SPs in the real-time scale and under practical exploitation conditions. This system should maintain functions of statistical data storage in the real time to provide their analysis as well as check up the efficacy of various algorithms for power extraction from SP.

Optimization of using the electric energy will enable to more exactly predict the possible potential of solar generation for a specific exploitation place and chosen type of photoelectric converters. The data obtained as a result of this system operation will provide not only acquisition of statistical data about the produced and consumed electric energy but also estimate the amount of electric energy that can be produced by SPs in future, optimize the area of SPs, capacities of energy accumulators, develop more efficient algorithms for operation of electronic circuits providing energy extraction.

The results of performed work can be used both in designing a new LED illumination systems and developing the solar photoelectric stations of various purposes.

2. Requirements to functional capabilities of intelligence systems for controlling and governing the solar panels

The solar batteries based on poly- and monocrystalline silicon are the most widely spread in the market of these facilities. Their fraction reaches approximately 90%. Since the forbidden gap of silicon is 1.121 eV, photons of solar light that contribute to generation of electricity (*i.e.*, the photoactive ones) should have the wavelength λ less than 1100 nm (energy $E > 1.121$ eV).

Increasing the value of energy illuminance at the photoreceiving surface proportionally increases the value of generated photocurrent and power, as a sequence. Since one separate solar element provides the open-circuit voltage 0.6–0.7 V, then the solar battery (SB) consists, as usual, of 36–80 solar elements connected in series to obtain the necessary rated output voltage 18–60 V (Fig. 1).

The current-voltage characteristics of SB (Fig. 2) at any illuminance levels consist of three parts: horizontal, bend and monotonic drop. The dependence of generated power on voltage (Fig. 3) is characterized by typical parts

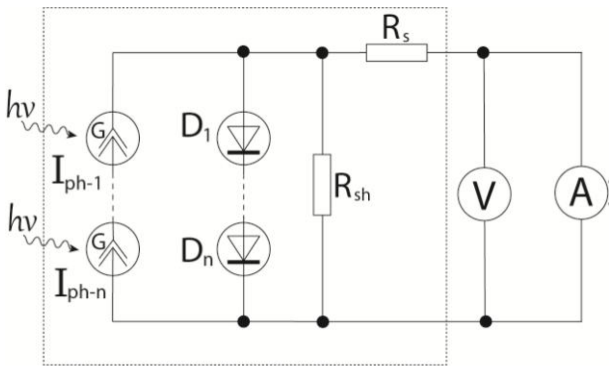


Fig. 1. Equivalent circuit of photoelectric battery with the external loading resistance R_L and measuring circuit. R_S – series (internal) resistance of SB; R_{sh} – shunt resistance of SB.

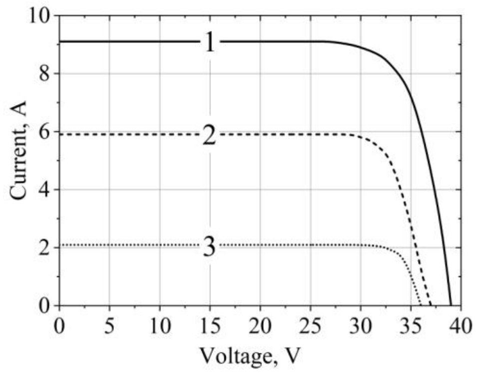


Fig. 2. Current *vs* voltage dependences for the solar battery LR6-60HV-290M [22] produced by the firm "LongiSolar" at the values of illuminance: *1* – 1000, *2* – 600 and *3* – 200 W/m^2.

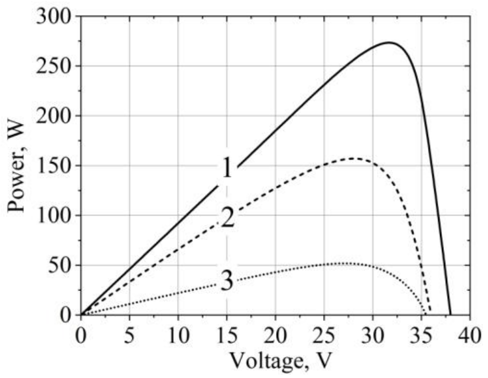


Fig. 3. Output electric power *vs* volage dependences for the solar battery LR6-60HV-290M [22] produced by the firm "LongiSolar" at the values of illuminance: *1* – 1000, *2* – 600 and *3* – 200 W/m^2.

of growth, decay and extremum between them, which approximately corresponds to the bend part in the current-voltage dependence.

Analyzing the current-voltage characteristics and dependences of output electric power on voltage, one can draw the conclusion that this power and efficiency of solar batteries depend *de facto* on the loading resistance.

When testing the solar batteries, it is usually determined the rated output electric power P_{SP} and efficiency in accord with standards for the operating point that corresponds to the maximum in the dependence of power *versus* voltage. This operating point is defined by the value of loading resistance that can be calculated using the following expression:

$$R_L = V_{\max}/I_{\max} \qquad (1)$$

where $V_{\max}$ and $I_{\max}$ are, respectively, the voltage and current at the operating point. When lowering the value of loading resistance from its optimal one, the operating point shifts to the left, and the output power decreases approximately obeying the linear law (Fig. 2). When the value of loading resistance grows relatively to its optimal value, the output power sharply drops (Fig. 3).

Designing the systems where solar generation will be used, it should be also taken into account the features of SB functioning, namely: the essential dependence of generation parameters not only on the level of energy illuminance of SB but on its temperature as well (Fig. 4).

With account of the abovementioned dependences, photoelectric modules are tested under the following standard conditions AM1.5: temperature T = 25 °C, energy illuminance 1000 W/m^2, standardized spectrum of the radiation source (Sun simulator). Abbreviation AM1.5 means "atmospheric mass equal to 1.5". In dependence on the Sun height above the horizon, solar light passes different ways to the Earth surface: it is the least when Sun is in its culmination (AM1), and is the longest at the sunrise and sunset (AM6). The value of AM can be calculated using the following expression:

$$\text{AM} = 1/\cos(\theta), \qquad (2)$$

where θ is the angle between the normal to the Earth surface and the direction to the Sun.

The standardized spectrum AM1.5G (G – total, global, including both direct and scattered components) corresponds to the angle of incidence 48° from the normal under some averaged conditions (humidity, CO_2 concentration and so on) [23].

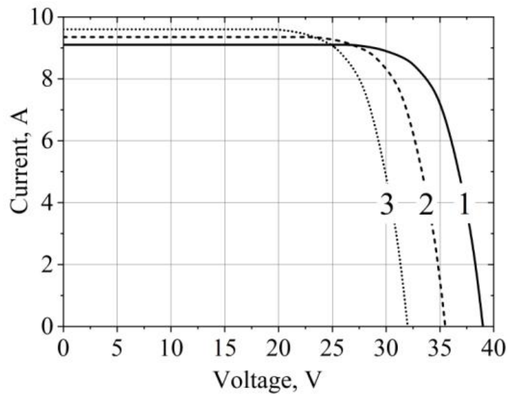


Fig. 4. Dependences of the current on voltage for SB LR6-60HV-290M [22] produced by the company "LongiSolar" under different SB temperatures: *1* – 25, *2* – 45 and *3* – 75 °C.

But real conditions for exploitation of photoelectric modules differ essentially from the standard ones, in particular, by the value of energy illuminance, temperature and spectrum.

The temperature of SB T_{SP} is mainly determined by the air temperature, level of energy illuminance and wind velocity [24]:

$$T_{SP}(°\mathrm{C}) = 0.943T_A + 0.0195E - 1.528V + 0.3529, \quad (3)$$

where T_A is the air temperature, °C; E – energy illuminance, W/m^2; V – wind velocity, m/s.

With account of the multi-parametric character of the tasks when determining the maximum efficiency of SB operation, it is important to create the systems for monitoring and governing that would be capable to optimize the regimes of SB exploitation as well as perform measurements of operation parameters under real conditions in the standalone mode. These intelligence systems should have the following functional capabilities:

- to provide an optimal operation regime for SB by changing the load resistance;
- to perform measurements of instant values of voltage and current inherent to SB;
- to provide the possibility of connecting the sensors for measuring parameters both of ambient medium and in arbitrary amount of points near the SB surface (temperature, humidity, wind velocity, *etc*);
- to carry out the automatic storage of measured data.

Up to date, production of solar elements reaches a considerable scale, the same is valid to the amount of producers of SBs, which causes the respective number of variations in their constructions. The analysis of a wide variety of industrial SBs indicates that performances of these systems should provide operation of batteries at the generated voltages at least 60 V.

With account of the mentioned above, it seems purposeful to use in investigations individual monitoring systems for every SB, the rated power of which does not exceed, as a rule, 600 W, which corresponds to the current value 9…10 A. Therefore, this intelligence system should provide optimization of the energy efficiency and respective measurements within the ranges of the following electric parameters: voltage 0…60 V, current 0…10 A. To create such an intelligence system, it is necessary to solve a number of hardware/software tasks.

3. The function of intelligence system providing determination of loading parameters inherent to SB

Under real exploitation conditions, in dependence on weather or day time the energy illuminance of SBs can change within wide limits, from 0 up to 1000 W/m^2. In so doing, the photocurrent can decrease in proportion to the value of illuminance, and the current–voltage characteristics (Fig. 2) shift down, optimal loading resistance grows, maximum of output power ($P_{\max}$) reduces and moves to the side of lower voltages.

Another important feature of these dependences is that the curve does not essentially change its shape with changing the illuminance value but changes its position, which causes the necessity to choose a new loading resistance that could provide the maximum efficiency in power extraction. Thereof, it follows that the function of permanent tuning the operation regime of SBs is the very important one for the intelligence system of monitoring and governing to satisfy the following requirements:

the necessity to keep with electronic facilities an optimal value of loading resistance R_L accordingly to the SB surface illuminance;

if it is impossible to keep the optimal value of R_L, then more energy efficient is operation at R_L values lower than the optimal one, in the linear part of power *vs* voltage dependence, within the range of lower voltages.

Solution of these tasks is possible when using the described above intelligence systems that are capable to perform automated tuning the R_L value to provide the highest level of power generation under currently conditions. In the point of maximal efficiency, the value of power generation derivative with regard to the voltage is equal to zero [25].

Since in the majority of cases transformation of the energy from SBs is carried out using pulse-duration modulation (PDM) converter, the output power of PDM-converter depends on its duty cycle D [26]. Respectively, it is reasonable to assume that successive D-values are related to one another by the following expression:

$$D_k = D_{k-1} \pm \Delta D, \quad (4)$$

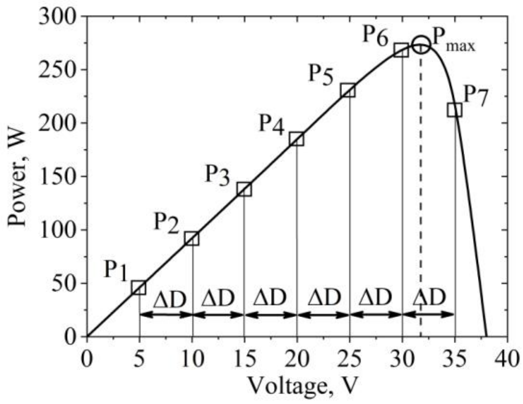
where D_k is a new value of duty cycle, D_{k-1} – its previous value, ΔD – step of duty cycle change.

In accord with the said above, the main task in the process of regulation will be finding the step for changing the value of duty cycle. With this aim, it should be measured the voltage and current of SB, which enables to determine the magnitude and sign of the power change.

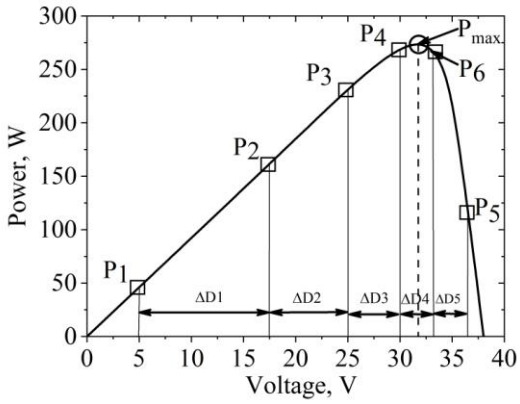
To change the duty cycle and find a maximal power, one can use a step with a constant value [27, 28], as it is shown in Fig. 5a. The deficiency of this approach is inaccuracy of finding the value D (that corresponds to the loading resistance) to obtain the maximal efficiency when using SBs.

However, this method seems to be the simplest in realization. Another method for tuning the duty cycle is application of a variable step [28, 29] (see Fig. 5b). In this approach, the system should change its step in dependence on the steepness of changes in the SB output power. In the step calculation module of this system, one can use PI and PID algorithms of regulator [30, 31] with the predicted maximal value.

In the developed system, to determine the duty cycle it seems purposeful to use the variable step, *i.e.*, to apply the PID regulator:



a)



b)

Fig. 5. (a) Finding the point P_{max} by using a fixed step, and (b) the same operation with a variable step.

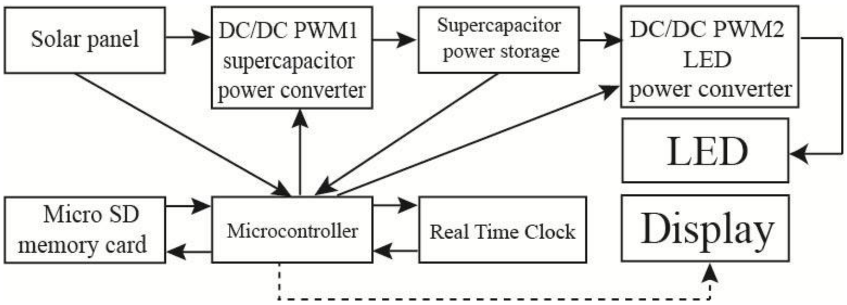


Fig. 6. Block-diagram of the offered intelligence system for monitoring and governing SB to provide power supply of a LED luminaire.

$$D = k_1 P + k_2 \int P dV + k_3 \frac{dP}{dV}, \quad (5)$$

where k_1 is the coefficient of proportional component, k_2 – coefficient of integrated component, k_3 – coefficient of differential component.

The main feature of our approach is variation of these PID regulator coefficients in dependence on changes in SB output power, which enables to reduce the time for finding the optimal *D*-value and to increase the efficiency of using the energy generated by SB.

4. Development of the intelligence system for monitoring and governing the SB energy efficiency to power LED luminaires

The main tasks in designing the intelligence system are as follows: studying the solar activity in a specific territory, registering the energy produced by SB, providing operation of LED sources in the rated regime under direct using the energy generated by SB, accumulation of this energy in supercapacitors, when the level of solar generation is low.

The obtained values of electric power generated by SB under real conditions will enable to estimate the capacitance of supercapacitors, which is capable to provide reliable functioning of real systems and check up the efficiency of system operation algorithms at low levels of solar generation. The important requirement to this system is its efficiency. Therefore, when designing this system, it was set the task to provide the efficiency value no less than 0.9 at the rated SB power.

Fig. 6 shows the developed block-diagram of such an intelligence system for monitoring and governing the solar battery aimed to power the LED luminaire. With account of considerable complexity, great data arrays, and multi-functional character of the offered system, for its realization it is purposeful to apply a microcontroller as a main governing module of the system.

This microcontroller should satisfy the following requirements: speed capability, productivity, memory capacity for programs and registration, main memory, energy saving, as well as availability of hardware capabilities for transforming, transmitting and receiving information, and governing the signals. This list of requirements can be supplemented with necessary reliability, wide accessibility, availability of wireless data communications protocol with external facilities, and the possibility of power supply under low levels of consumption.

Taking into account the requirements listed above, it seemed purposeful to use the microcontroller PIC16LF1829 [32], which allows simultaneous connection to 18 digital input/output ports, 12 of which can serve as the analog ones. This controller has two built-in Master Synchronous Serial Ports that can operate in accord with the SPI and I2C protocols. Besides, it allows operation in accord with the protocol Enhanced Universal Synchronous Asynchronous Receiver Transmitter (EUSART). To provide a high operation speed, the microcontroller can operate at the frequency up to 32 MHz and can be re-switched by a special program to the frequency 31 kHz, which provides transition to the regime of lower consumption, when its feeding current is reduced down to 600 nA. Besides, when the necessity of long-term operation is absent, the microcontroller can be re-switched to the sleep mode (consumed current will be only 20 nA) and programmed to be returned to the operation mode after a special external signal. The microcontroller contains 14 kB program memory, 1 kB SRAM and 256 B EEPROM.

The analog-digital converters with the resolving power 10 bit built into this microcontroller allow measuring the values of output voltage and output current, which provides determination of the instant power that is generated by SB under the set load and operation mode. Since different levels of illuminance and temperature of SB need different values of the optimal loading resistance, which corresponds to the maximal generated energy extracted into the external circuit, then it is necessary to regulate the power by changing the loading resistance. To reach that, it is offered to apply the PDM1 converter HV9911. This converter enables to connect SB with the power supply up to 250 V.

It provides wide possibilities for further improvements of the system under combined connection not only one but several SBs, which allows widening its applications for series connection of SBs. Series commutation of SBs can be applied for lowering the current in connecting wires, which lowers losses in these wires caused by Joule heating in the system of high power. The advantage of this converter is the possibility to operate in accord with topologies Buck, Boost, Buck-boost and provide at the output a stable current. This feature is very important, because it is necessary to control the load power of SBs, power supply of LEDs and charge of supercapacitors during operation.

Also, the PDM1 converter HV9911 allows changing the frequency of generation, which enables to tune the circuit for reaching the optimal efficiency within the whole range of input voltages for the chosen elemental base. The PDM1 converter of power supply from supercapacitors has a separate port for connection with the microcontroller that governs PDM1 with signals of a different off-duty ratio, which defines the output current of this converter.

The microcontroller changes the output current of converter within the range 0.01…6 A and measures the value of input voltage and current from SB. Knowing the value of input power, one can determine its maximal value and operate at this value. When the illuminance or temperature of SB is changed, the microcontroller will determine a new optimal value of loading resistance.

A special feature of using supercapacitors as energy accumulators is the need to limit the charging voltage when reaching the charge limit [33]. To avoid exceeding the voltage, foreseen in this system is the feedback of PDM1 that enables to measure the output voltage and additional control of it by the microcontroller that through the governing output switches-off the PDM1 converter.

The PDM2 converter, which supplies LEDs, is designed in such a manner that enables to provide the rated power supply of LEDs, and, if necessary, the microcontroller *via* the governing PDM2 can reduce the output power and even switch-off it. This capability is used when reaching the critical discharge of supercapacitors.

The intelligence system for monitoring and governing possesses its capability to store in a real-time scale the values of generated voltage and current (power) of SB, voltage on supercapacitors, consumption current of PDM2 converter that supplies LEDs. It is provided by a separate module for time reading, which gives data in the following format: seconds, minutes, hours, day of the week, month, and year. Data transmission from this module to the microcontroller is realized using the 12C protocol. This module has its own supply battery, which allows to power this module in absence of solar generation, and prolongs time reading. Being based on the data obtained from this module as well as the measured voltage and current, the data packet is formed. These data are recorded using the microSD card in accord with the SPI protocol. Application of the microSD card enables to easy transmit the data from the controlling system to the computer, which facilitates the following analysis.

To tune and display ordering information, there is a possibility to connect the display with the monitoring system operating accordingly to the 12C protocol.

With this aim, foreseen in the construction is an additional port. The microcontroller is also equipped with two buttons that provide to tune time reading and microcontroller programs without using additional equipment.

One special feature more in the developed intelligence system is the possibility of autonomous operation, *i.e.*, all the system modules are supplied from the same solar battery. In the case of insufficient solar generation, the microcontroller transfers to the sleep mode, when its consumption current is lowered down to 100 nA, then the events of falling asleep and awakening (when generation is recovered) are registered in the microSD journal. This function allows very long operation of the system without connection with any external energy sources, which enables to use it for statistical data acquisition in any places.

In accord with the offered block-diagram of intelligence monitoring system, we developed the electronic circuit and model shown in Fig. 7.

As seen from Fig. 7, in the layout of developed intelligence system the connectors and thermally loaded electronic elements (transistors and diodes) are placed along the perimeter of printed-circuit board, which enables to easily connect to commutation card slots and the system for cooling the power elements.

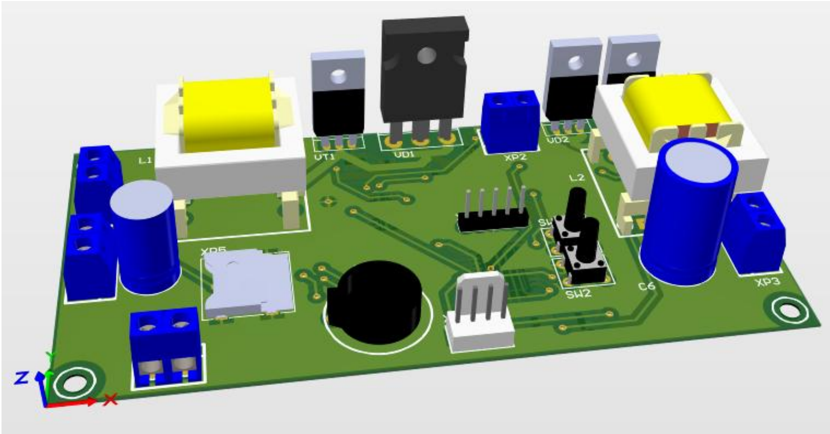


Fig. 7. Developed layout for the electronic circuit of intelligence monitoring and governing system.

5. Conclusions

Under real conditions of exploitation, in dependence on weather, there observed are different levels of energy illuminance of solar batteries within the wide range from 40 up to 1000 W/m^2, and the efficiency of batteries essentially depends on the parameters of ambient medium (air temperature, velocity and direction of wind) as well as peculiarities of their installation. Therefore, the most efficient use of electric energy generated by SB, determination of its power and way of installation requires acquisition of data about real generation parameters and adequate analysis of these data. All these requirements can be satisfied using the developed specialized intelligence monitoring and governing system operating in the autonomous mode.

The electric power produced by SB is proportional to the energy illuminance. Changes in the energy illuminance during SB operation require from the systems extracting the generated power permanent tuning of the loading resistance to provide the maximum output power.

The developed intelligence system for monitoring and governing the SB energy efficiency for supplying the LED luminaires allows on the base of directly measured generation parameters (voltage and consumption current, temperature) in a real-time scale to analyze capabilities of SB generation for the chosen location. Also, it can perform the statistical account of the produced electric energy and provide prediction of its generation in real systems. Besides, the analysis of complex data will enable to optimize conditions of SB generation as well as coordinate it with the power consumption. It is worth to note that the developed system can operate in the autonomous mode, which allows its using in any locations.

Realized in the offered intelligence system is finding the optimal value of loading resistance to reach the maximal power, which is performed using the algorithm of variable step with the predicted maximum value. Tuning the value of off-duty ratio for PDM converter is carried out with the algorithm of PID regulator.

The direction of further investigations is manufacturing the experimental sample of the offered intelligence system for monitoring and governing the combined electric supply of power LED luminaires with heat pipes [3, 5, 9] from solar batteries.

Acknowledgments

The present work was supported by the National research foundation of Ukraine (project No 2020.01/0216).

References

1. Pekur D.V., Sorokin V.M., Nikolaenko Y.E. Features of wall-mounted luminaires with different types of light sources. *Electrica*. 2021. **21**, No 1. P. 32–40.
https://doi.org/10.5152/electrica.2020.20017.
2. Schubert E., Kim J.K. Solid-state light sources getting smart. *Science*. 2005. **308**. P. 1274–1278. https://doi.org/10.1126/science.1108712.
3. Pekur D.V., Sorokin V.M., Nikolaenko Yu.E. Experimental study of a compact cooling system with heat pipes for powerful led matrix. *Tekhnologiya i Konstruirovanie v Elektronnoi Apparature*. 2020. № 3-4. P. 35–41 (in Ukrainian). http://dx.doi.org/10.15222/TKEA2020.3-4.35.
4. Ursaki A. Development of chip-on-board LED modules by the example of matrix evolution from citizen electronics. *Sovremennaja svetoteknika*. 2018. No. 2. P. 20–22 (in Russian).
5. Pekur D.V., Sorokin V.M., Nikolaenko Yu.E. *et al.* Electro-optical characteristics of an innovative LED luminaire with an LED matrix cooling system based on heat pipes. *Semiconductor Physics, Quantum Electronics and Optoelectronics*. 2020. **23**, No 4. P. 415–423. https://doi.org/10.15407/spqeo23.04.415.

6. Li J., Tian W., Lv L. A thermosyphon heat pipe cooler for high power LEDs cooling. *Heat Mass Transfer.* 2015. **52**, No 8. P. 1541–1548. http://dx.doi.org/10.1007/s00231-015-1679-z.
7. Kiseev V., Sazhin O. Heat transfer enhancement in a loop thermosyphon using nanoparticles/water nanofluid. *Int. J. Heat Mass Transfer*. 2019. **132**. P. 557–564. https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.109.
8. Nikolaenko Yu.E., Pekur D.V., Sorokin V.M. Light characteristics of high-power LED luminaire with a cooling system based on heat pipe. *SPQEO*. 2019. **22**, No 3. P. 366–371. https://doi.org/10.15407/spqeo22.03.366.
9. Pekur D.V., Nikolaenko Yu.E., Sorokin V.M. Optimization of the cooling system design for a compact high-power LED luminaire. *SPQEO*. 2020. **23**, No 1. P. 91–101. https://doi.org/10.15407/spqeo23.01.091.
10. Sosoi G., Vizitiu R.S., Burlacu A., Galatanu C.D. A heat pipe cooler for high power LED's cooling in harsh conditions. *Proc. Manufacturing*. 2019. **32**. P. 513–519. https://doi.org/10.1016/j.promfg.2019.02.247.
11. Pekur D.V., Sorokin V.M., Nikolaenko Yu.E. Thermal characteristics of a compact LED luminaire with a cooling system based on heat pipes. *Therm. Sci. Eng. Progress*. 2020. **18**. Art. No 100549. https://doi.org/10.1016/j.tsep.2020.100549.
12. Prisniakov K., Marchenko O., Melikaev Yu., Kravetz V., Nikolaenko Yu., Prisniakov V. About complex influence of vibrations and gravitational fields on serviceability of heat pipes in composition of the space-rocket systems. *54th Intern. Astronaut. Congress of the Intern. Astronautical Federation (IAF), the Intern. Academy of Astronautics and the Intern. Institute of Space Law, Intern. Astronaut. Congress (IAF).* Bremen, Germany. 2003. **1**. P. 1571–1580. http://dx.doi.org/10.2514/6.IAC-03-I.1.10.
13. Kim J.-S., Bae J.-Y., Kim E.-P. Analysis of the experimental cooling performance of a high-power light-emitting diode package with a modified crevice-type vapor chamber heat pipe. *J. Korean Soc. Marine Eng.* 2015. **39**, No. 8. P. 801–806. http://dx.doi.org/10.5916/jkosme.2015.39.8.801.
14. Babaev V.M., Govorov P.P., Govorov V.P., Korol O.V. Energy saving in the systems of heat supply and lighting of buildings. *Budivelni konstrukcii.* 2013. Issue 77. P. 169–173 (in Ukrainian). http://nbuv.gov.ua/UJRN/buko_2013_77_33.
15. Nikolaenko Yu.E., Kravets V.Yu., Naumova A.N., Baranyuk A.V. Development of the ways to increase the lighting energy efficiency of living space. *Int. J. Energy Clean Environment.* 2017. **18**, No 3. P. 275–285. https://doi.org/10.1615/InterJEnerCleanEnv.2018021641.
16. Chiradeja P., Yoomak S. & Ngaopitakkul A. Economic analysis of improving the energy efficiency of nanogrid solar road lighting using adaptive lighting control. *IEEE Access*. 2020. **8**. P. 202623–202638. http://dx.doi.org/10.1109/access.2020.3035702.
17. Kolomzarov Yu.V., Kostylyov V.P., Sorokin V.M. *et al.* Environmental issues of lighting and prospects of energy saving LED lighting systems with combined power supply. *Tekhnologiya i Konstruirovanie v Elektronnoi Apparature.* 2020. No 5-6. P. 3–9. (in Ukrainian) http://dx.doi.org/10.15222/tkea2020.5-6.03.
18. Borkowski P., Pawłowski M. Zasilanie energooszczędnych źródeł światła poprzez systemy zasobnikowe. *Przeglad Elektrotechniczny*. 2013. **89**, No 1A. P. 21–24.
19. Pekur D.V., Kolomzarov Yu.V., Kostylyov V.P. *et al*. Supercapacitor energy storage systems for lighting systems with combined power supply. *Tekhnologiya i Konstruirovanie v Elektronnoi Apparature.* 2021. No 1-2. P. 3–9 (in Ukrainian). http://dx.doi.org/10.15222/TKEA2021.1-2.03.
20. *Applied Photovoltaics*. Eds S.R. Wenham, M.A. Green, M.E. Watt, R. Corkish. 2nd edition. Routledge, 2006.
21. *Practical Handbook of Photovoltaics: Fundamentals and Applications.* Eds A. McEvoy, T. Markvart and L. Castañer. Amsterdam, Elsevier, 2012. https://doi.org/10.1016/C2011-0-05723-X.
22. https://si-datastore.s3.us-west-2.amazonaws.com/documents/mYPaaJCiWlUavDddNwF5M3FnnBf35kzFsONw7xH0.pdf (reference date: 08.02.2021).
23. *ASTM G173 – 03(2020) Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface.* https://www.nrel.gov/grid/solar-resource/spectra.html (reference date: 08.02.2021).
24. Muzathik A.M. Photovoltaic modules operating temperature estimation using a simple correlation. *Int. J. Energy Eng*. 2014. **4**, No 4. P. 151–158.
25. Hohm D.P. and Ropp M.E. Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed. *28th IEEE Photovoltaic Specialists Conference – 2000* (Cat. No.00CH37036). Anchorage. AK. USA. 2000. P. 1699–1702. https://doi.org/10.1109/PVSC.2000.916230.
26. Mei Q., Shan M., Liu L., Guerrero J.M. A novel improved variable step-size incremental-resistance MPPT method for PV systems. *IEEE Trans. Industr. Electron*. 2011. **58**, No 6. P. 2427–2434. https://doi.org/10.1109/TIE.2010.2064275.
27. Chen Y.-T., Lai Z.-H., Liang R.-H. A novel auto-scaling variable step-size MPPT method for a PV system. *Sol. Energy*. 2014. **102**. 247–256. https://doi.org/10.1016/j.solener.2014.01.026.

28. Ouoba D., Fakkar A., El Kouari Y. *et al*. An improved maximum power point tracking method for photovoltaic system. *Opt. Mater*. 2016. **56**. P. 100–106. https://doi.org/10.1016/j.optmat.2016.01.026.
29. Ahmed E.M., Shoyama M. Highly efficient variable-step-size maximum power point tracker for PV systems. *3rd International Symposium on Electrical and Electronic Engineering* (ISEEE). 16–18 September 2010. P. 112–117. https://doi.org/10.1109/ISEEE.2010.5628532.
30. Prodic A., Maksimovic D. Design of a digital PID regulator based on look-up tables for control of high-frequency DC-DC converters. *2002 IEEE Workshop on Computers in Power Electronics, 2002*. Proc. IEEE. Mayaguez, PR, USA. P. 18–22. https://doi.org/10.1109/CIPE.2002.1196709.
31. Santibañez V., Camarillo K., Moreno-Valenzuela J., Campa R. A practical PID regulator with bounded torques for robot manipulators. *Int. J. Control, Automation and Systems*. 2010. **8**, No 3. P. 544–555. https://doi.org/10.1007/s12555-010-0307-4.
32. Microchip Technology Inc. https://www.microchip.com/wwwproducts/en/PIC16F1829 (reference date: 08.02.2021).
33. Berrueta A., Ursúa A., Martín I.S., Eftekhari A., Sanchis P. Supercapacitors: electrical characteristics, modeling, applications, and future trends. *IEEE Access*. 2019. **7**. P. 50869–50896. https://doi.org/10.1109/ACCESS.2019.2908558.

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Інтелектуальна система контролю і керування енергоефективністю сонячних батарей для живлення світлодіодних освітлювальних приладів

В.І. Корнага, Д.В. Пекур, Ю.В. Коломзаров, В.П. Костильов, В.М. Сорокін, Р.М. Коркішко, Ю.Е. Ніколаєнко

Анотація. Розроблено принципи побудови системи контролю і керування енергоефективністю сонячних батарей для електроживлення світлодіодних освітлювальних приладів, що дозволяє найефективніше використовувати електроенергію, генеровану сонячними батареями, в реальному часі, зберігати дані про функціонування системи та проводити комплексний аналіз. Оптимізація використання генерованої сонячними батареями електроенергії буде визначати максимально можливу потужність у кожний конкретний момент та автоматично налаштовувати її споживання. Отримані в результаті роботи такої системи комплексні дані буде можливо використовувати не тільки для статистичної фіксації фактично виробленої та спожитої електроенергії, а також для прогнозування можливої кількості енергії, генерованої сонячними батареями в подальшому. Аналіз результатів дозволить оптимізувати площу сонячних батарей та більш точно виконувати визначення параметрів електронних компонентів як для систем освітлення, так і при створенні сонячних фотоелектростанцій різного призначення.

Ключові слова: фотоперетворювачі сонячної енергії, діагностика сонячних батарей, системи освітлення, суперконденсатори.