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STUDY OF OPERATING MODES OF A STAND-ALONE PHOTOVOLTAIC SYSTEM FOR OUTDOOR LIGHTING

*Stoyo Platikanov**, *Milko Yovchev*
Technical University of Gabrovo, Faculty of Electrical Engineering and Electronics, 4, H. Dimitar Str., 5300 Gabrovo, Bulgaria

Summary: Photovoltaic power supply of street lighting has been developing rapidly in recent years. A stand-alone photovoltaic (PV) system supplying light-emitting diode (LED) outdoor luminaires has been constructed in the Technical University of Gabrovo. A PV-LED system consists of a PV module, a storage battery, a solar controller, a LED lamp and a system for remote visualization of operating modes. Working processes for optimization of the night operating mode of LED luminaire have been studied. Data on electrical energy stored by the battery and consumed for lighting have been presented.
Keywords: PV-LED system, remote visualization, optimization, operating modes, experimental studies, electric power.

1. INTRODUCTION

Photovoltaic (PV) conversion is being more and more widely applied in order to satisfy the requirements of environmental protection in electricity production and to provide autonomy. Modern photovoltaic modules are introduced, new technologies emerge with the development of light-emitting diodes (LED) for outdoor lighting. The advantages of LED are the following: long-term service life, small size and capability to operate with vibrations, high light efficiency, favourable colour rendering index [1,2].

This paper deals with the modes of storage battery charging and discharging during the operation of a photovoltaic system with a controller for street LED lighting. With the development of PV-LED systems, it is necessary to improve their operating modes, which requires studying and making thorough analyses. This has resulted in enhancing individual engineering characteristics of certain components and optimization of functional capacities of the manufactured commercial solar controllers.

2. EXPERIMENTAL STUDIES AND OUTCOME ANALYSIS

Figure 1 shows the arrangement and position of components which are included in the PV-LED system built.

The photovoltaic module which converts daylight into electrical energy has a power of 80 Wp. It consists of 9x4 photovoltaic cells built of monocrystalline silicon.

The storage battery mounted in a metal box (Figure 1), has a capacity of 100 Ah and 12 V voltage. It is designed to store the electrical energy produced by the PV module during the daytime when it is charged and supply LED luminaire with it at night (it is discharged) [3].

The street luminaire mounted in the PV-LED system has a power of 18 W and is built of LED matrix 4x10 (Figure 2). It is supplied with direct 12 V voltage, provided by the storage battery.

The operating modes of the PV-LED street system are controlled by a solar controller of MPPT-TRACER 1210 RN type. It is supplied with 12 V_{DC} rated voltage; it has rated current of 10 A. The maximum input voltage is 100 V (for no-load running of PV module), and the input power to the controller is 120 W. It has the protection against currents through the load higher than 35 A. Its own consumption is low – up to 16 mA, and the operating temperature range is from –30° C to +60° C. The duration of consumer operation – a street LED luminaire with 18 W power can be set within the range of 1 to 15 hours. The solar controller has 8-pin port RJ-45 to be connected to LCD display.

The controller has the function: Maximum Power Point Tracer (MPPT), which is automatic tracing of the point with maximum power from V-A

* Corresponding author: platikanov@yahoo.de

characteristic of PV module which enhances the efficiency of the system [1].

The information on electric processes taking place and on studying the operating modes of PV-LED system from the solar controller is sent to LCD display MeTer MT-2 by means of RJ-45 connector along LAN cable. Figure 3 shows the symbols on the display and their meanings.

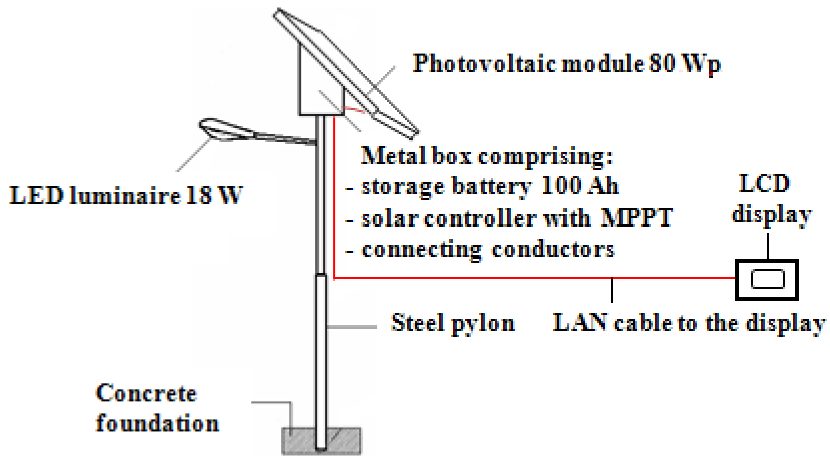

Figure 1. Arrangement of PV power supply of a LED street luminaire

Figure 2. Street luminaire with LED matrix

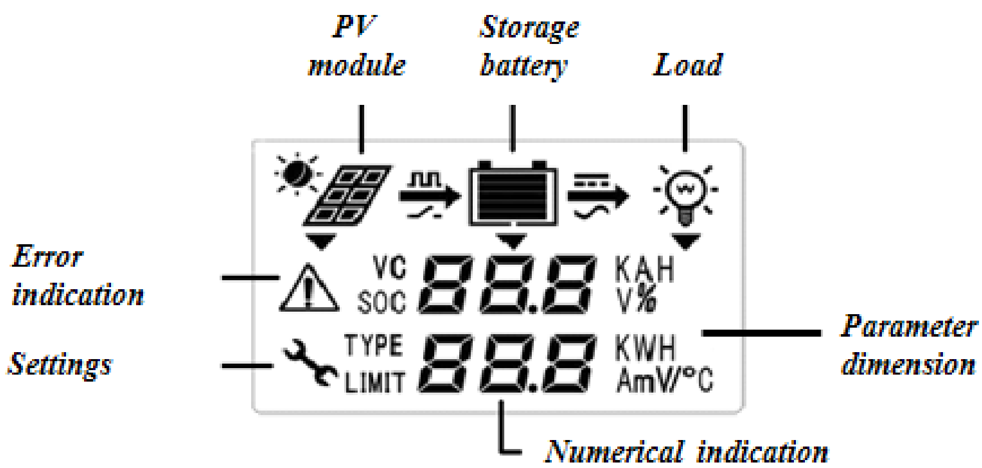

Figure 3. Meanings of symbols on LCD display MeTer MT-2

LCD display MeTer MT-2 has two LED indicators. When the battery is charged in the daytime, a green LED is lit below Charge. When there is an error, a red LED is lit below Error [1].

The storage battery charge and discharge modes during the winter months are of particular interest. Owing to weather conditions and short days the battery cannot be fully charged.

In Table 1 by means of LCD display MeTer MT-2 the results of experimental measurements are presented taken during battery discharge from the moment of switching on the street LED luminaire by the controller in the evening on 08 March 2013. Column 2 of Table 1 presents the values of PV module voltage U_{PV} [V]; columns 3 to 6 show the values measured of the discharging storage battery: voltage U_{BAT} [V], current I_{BAT} [V], temperature T_{BAT} [^oC] and state of charge SOC [%]. The voltage U_{LED} [V] and current I_{LED} [A] of the load are given in columns 7 and 8; the capacity [Ah] and the electrical energy [Wh], released by the storage battery and consumed by LED luminaire are presented in columns 9 and 10. The experimental reading of data on discharge mode took two hours (column 1).

Table 1. Discharge of storage battery through luminaire load (LED matrix 18 W/12 V_{DC}) at night. Date: 08 March 2013

Time of measurement	Voltage of PV module	Voltage, current, temperature and state of charge of storage battery with capacity of 100 Ah				Load voltage and current		Capacity and electrical energy released by the battery through the load	
	U_{PV} [V] I_{PV} = 0 A	U_{BAT} [V]	I_{BAT} [A]	T_{BAT} [^oC]	SOC [%]	U_{LED} [V]	I_{LED} [A]	[Ah]	[Wh]
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
18:47	1.6	13.0	0.0	17	62	0.0	0.0	0.0	0.0
18:50*	1.3	12.6	-7.3	18	50	12.6	7.3	0.0	0.0
18:51	1.1	12.6	-8.4	18	48	12.6	8.4	0.2	5.9
18:52	1.0	12.5	-8.9	18	46	12.5	8.9	0.4	8.3
18:53	0.9	12.5	-9.4	19	47	12.5	9.4	0.6	10.3
18:54	0.8	12.5	-9.9	19	46	12.5	9.9	0.7	12.4
18:55	0.8	12.4	-10.3	19	46	12.4	10.3	0.9	14.6
18:56	0.7	12.5	-9.7	19	47	12.5	9.7	1.1	16.7
18:57	0.7	12.4	-9.3	20	47	12.4	9.3	1.2	18.7
18:58	0.7	12.5	-8.7	20	47	12.5	8.7	1.4	20.6
18:59	0.7	12.5	-8.5	20	47	12.5	8.5	1.5	22.4
19:00	0.6	12.5	-8.3	20	48	12.5	8.3	1.6	24.3
19:05	0.6	12.5	-7.6	21	47	12.5	7.6	1.7	32.3
19:10	0.5	12.5	-6.9	21	48	12.5	6.9	3.0	39.5
19:15	0.6	12.5	-6.9	21	50	12.5	6.9	3.3	46.7
19:20	0.5	12.5	-6.7	21	48	12.5	6.7	4.2	53.7
19:30	0.5	12.4	-6.7	21	48	12.4	6.7	5.3	67.6
19:40	0.6	12.4	-6.7	21	46	12.4	6.7	5.6	81.5
19:45	0.6	12.4	-6.7	21	46	12.4	6.7	6.1	88.6
19:50	0.6	12.6	-3.6	21	50	12.6	3.6	6.7	95.0
20:00	0.6	12.6	-3.5	20	49	12.6	3.5	7.7	102.6
20:30	0.6	12.5	-3.5	19	46	12.5	3.5	8.9	124.5
20:40	0.6	12.5	-3.5	18	46	12.5	3.5	9.8	131.8

* - at 18:50 the load (LED luminaire with a power of 18W) is switched on and the storage battery discharge starts.

From the results obtained during measuring the processes in PV-LED luminaire by means of LCD-MeTer display, it was found that from the moment of switching on the load for an hour, the battery discharge current (which is equal to the current through the load) was considerably higher and with variable value. After 60 minutes have passed from starting the discharge, the same discharge current decreases considerably and sets up at approximately 3.5 A.

The results about an hour transition process when the current through the load is very high are presented in detail. LED luminaire is switched on at 18:50. The values of the load current (respectively the battery discharge current which has a negative sign) are considerably high during one hour. The data on the display are read and recorded each minute for 10 minutes when the current reaches its peak of 10.3 A at 18:55 and then it decreases (decreasing exponent) and it sets up within the range of 6.7 A to 6.9 A but it continues to be relatively high – Figure 4.

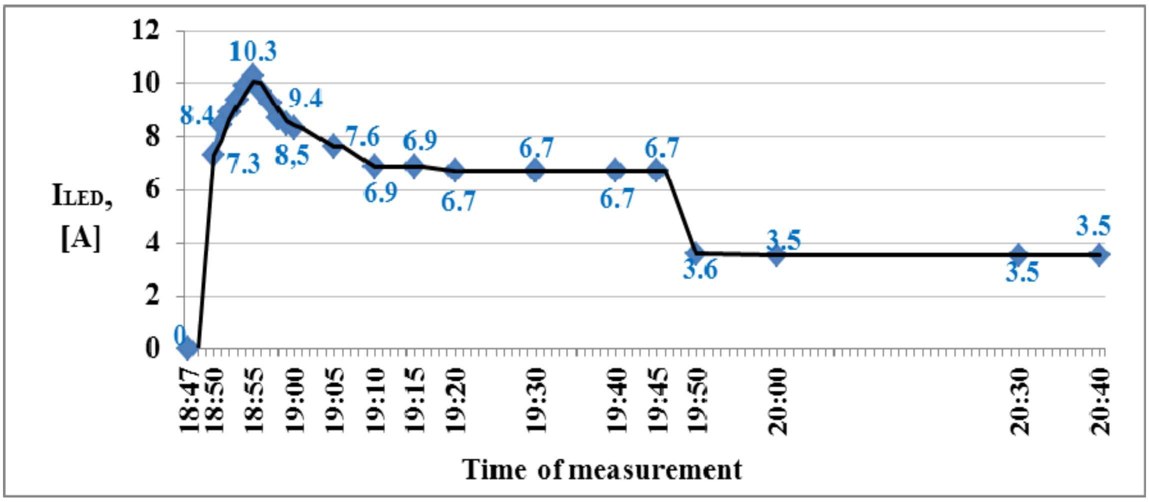

Figure 4. Variation in current I_{LED} through LED street luminaire

One hour after switching on the load, the current values decrease abruptly and they set up within 3.2 A to 3.6 A up to the very end of the load operation (it was found that the operation time has different duration for different night hours depending on accumulated electrical energy in the storage battery during daytime, i.e. on the state of charge which depends directly on solar radiation).

In the graph of current through load I_{LED} vs. time (Figure 4) a trend line is added with a mobile average value for the period of the selected series of data. This period is from the initial moment of reading - at 18:47 until the end of measuring – at 20:40. The reason for adding an additional line of trend is that long-term reading of the variation in electric current through the luminaire is used, combined with different frequency of obtained and recorded data. The values of the current are not recorded over the same time interval (step) in an x-axis. For some periods it is approximately constant and the recording is over longer intervals. For others (e.g. during the first 20 minutes from switching on LED luminaire) the variation is very dynamic, measuring and recording of values must be performed at very close intervals – the reading and recording of values of time on the graph is irregular. Owing to the trend line, a stable direction of current variation in time through load I_{LED} is observed and the required clearness of the obtained results achieved.

Variation in current through load in time is identical for the remaining night hours on other days (this was established experimentally) but the storage battery must be sufficiently charged so that the solar controller can allow switching on the load during the night.

Figure 5 shows the consumed electrical energy in [Wh] from the storage battery through the LED luminaire with 18 W power and variation in the state of charge SOC, [%] in the storage battery for 110 minute reading of its discharge.

When reading the state of charge (SOC in [%]) of the storage battery and consumed electrical energy in [Wh] by the luminaire at night, the trend line has been used again. In the period from 20:00 hrs to 20:30 hrs values are not recorded but the stable character of variation in two electrical parameters is known (a mobile average value has been set). Electrical energy from the storage battery through the luminaire varies along the increasing exponent. After 19:50h decreasing intensity of providing electrical energy was recorded which is explained by an abrupt decrease of discharge current (respectively consumed current) from this moment on (Figure 4).

LED luminaire is switched on and off by illumination control since the electrical voltage of PV module U_{PV} is proportional to ambient light (solar radiation intensity). It was established from experimental studies that LED luminaire switches on automatically in the evening when PV module voltage decreases below 1.3 V. Luminaire switches off again automatically in the morning (providing that the storage battery has enough capacity for the lamp to operate all night) at PV module voltage value: $U_{PV} \approx (1.1 \div 1.3)$ V (with an increasing variation because solar radiation intensity rises).

Table 2 presents the measurement results from charging in the daytime and discharging at night of the storage battery (capacity of 100 Ah).

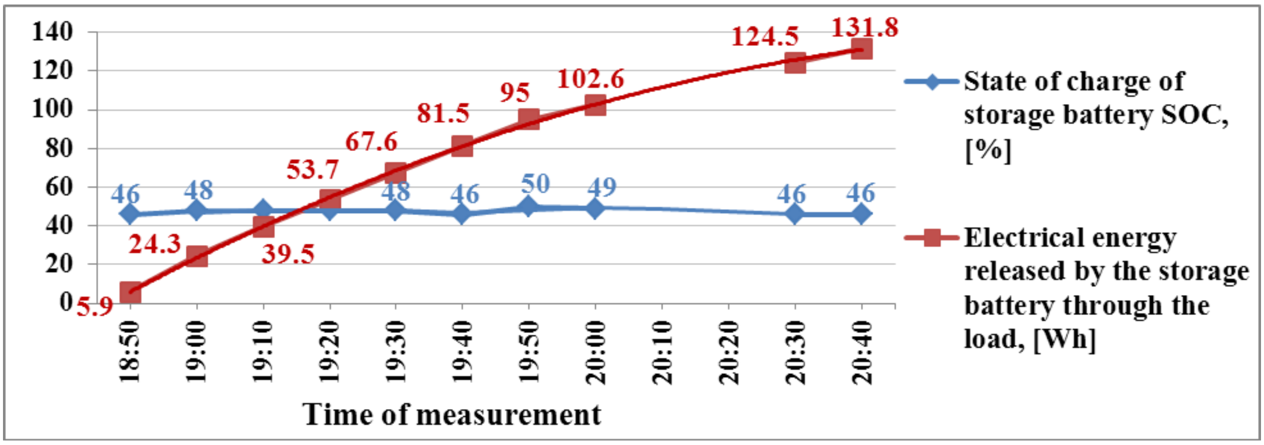

Figure 5. Variation in SOC and consumed electrical energy from the storage battery through street LED luminaire

Table 2. Operating modes of PV-LED system

Date, weather conditions	Charging of storage battery 100 Ah for 9 hours (when daylight is available) – from 8:00 to 17:00 hrs.		Discharging of storage battery 100 Ah for 6 hours (at night) – from 18:45 to 00:45 hrs.	
	Electrical energy produced by the PV module and stored in the battery, [Wh]	Capacity created by the PV module in the storage battery, [Ah]	Electrical energy from the storage battery to the LED luminaire with a power of 18 W, [Wh]	Capacity from the storage battery to LED luminaire with a power of 18 W, [Ah]
04.03.2013, sunny	266	13.700	243*	19.500*
05.03.2013, sunny	285	15.300	255	20.400
06.03.2013, cloudy	334	15.100	256	20.400
07.03.2013, changeable	168	14.600	241	19.400
08.03.2013, changeable	280	13.500	105*	10.500*
Total	1.333 kWh	72.200 Ah	1.100 kWh	90.200 Ah
Note: Values marked with * show that the storage battery discharges for 5 hours – from 18:45 to 23:50 hrs.				

At this time of the year – beginning of March, LED luminaire operates approximately for half of the night (from 18:50 to 00:40 hrs – for 6 hours), because the storage battery cannot be sufficiently charged. The main reasons are: short days, insufficient number of sunny hours and low values of global solar radiation compared to summer months.

Figure 6 presents a daily variation in global solar radiation Gl, [W/m^2] for averaged 10 minute values for four days at the beginning of March (04, 05, 07 and 08 March), when the operating modes of PV-LED system were analyzed. The data is obtained by Kipp & Zonen pyranometer and software for remote reading [5].

Figure 7 presents a diagram of electrical energy in [Wh] produced in the daytime and stored in the battery and then released by the battery and consumed through the load at night on certain days in March, 2013. Total values of stored and consumed electrical energy for this period are also shown.

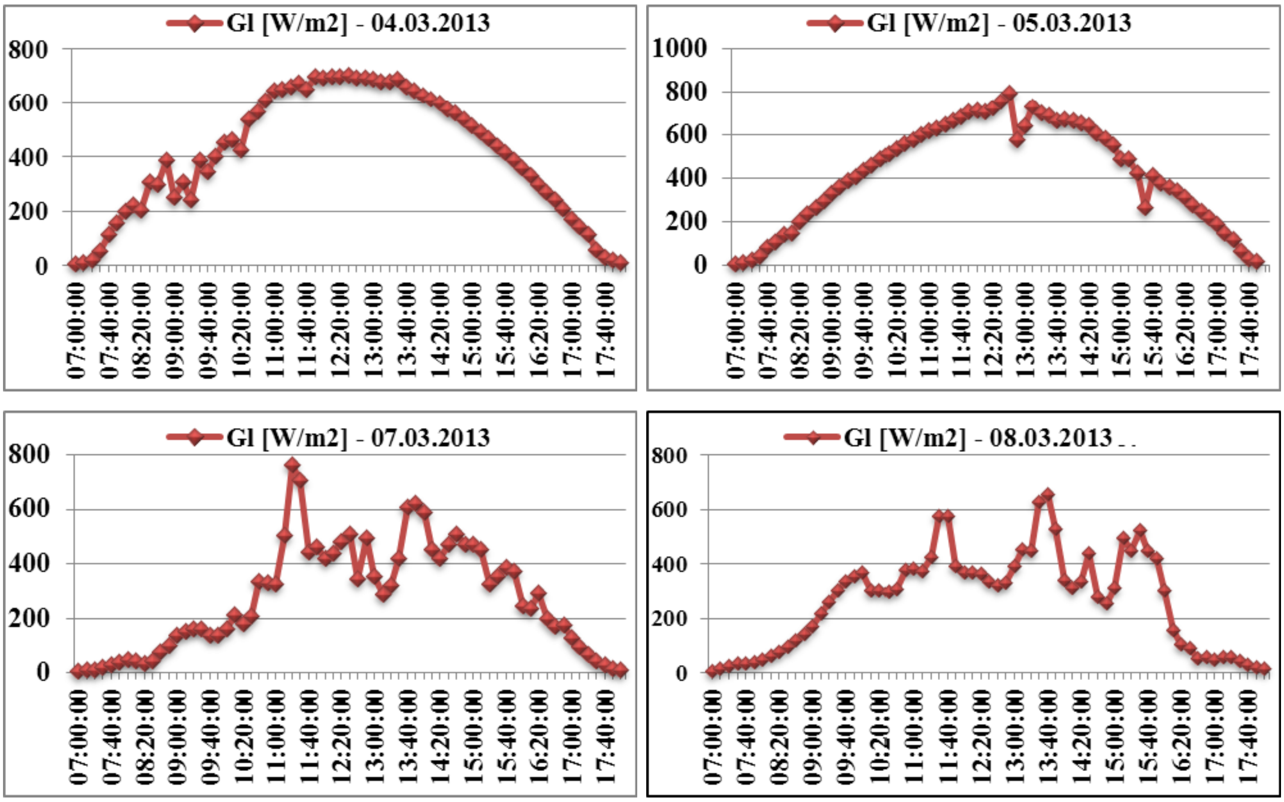

Figure 6. Variation in global solar radiation at averaged 10-minute values read by Kipp & Zonen pyranometer

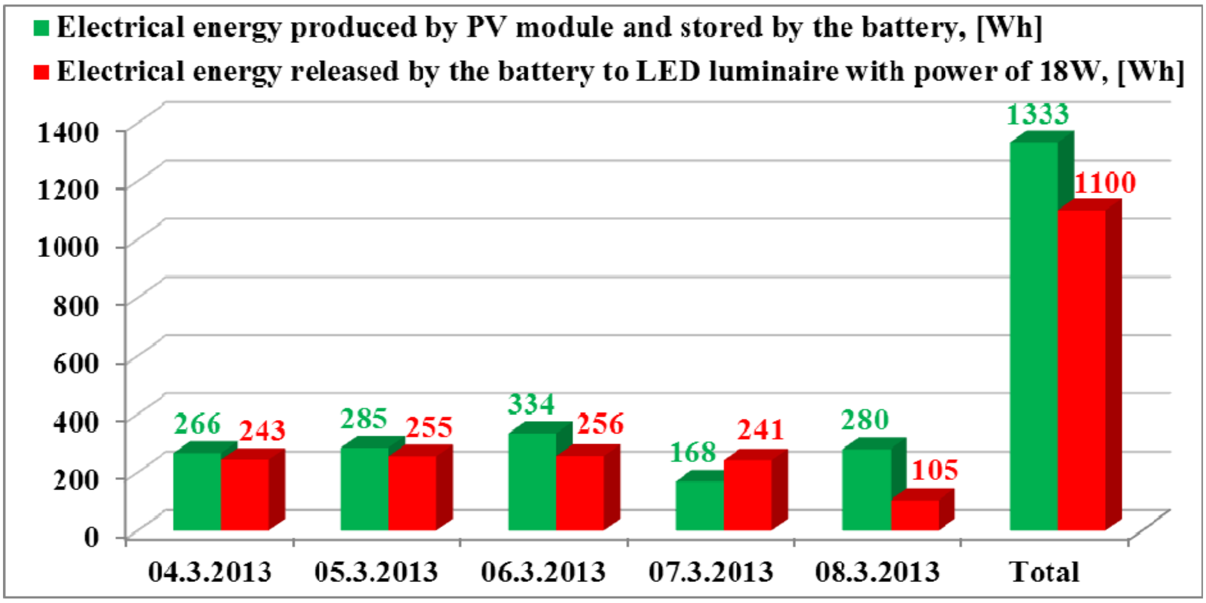

Figure 7. Electrical energy produced by the PV module, released by the storage battery and consumed through the LED load

Electrical energy produced by PV module depends on weather conditions in the daytime and sunny hours, while the value of electrical energy consumed – on the degree of charge in the storage battery and operation time of luminaire.

3. CONCLUSION

From the storage battery charge and discharge modes studied at the beginning of March (no snow) when accumulated electrical energy is not sufficient for the luminaire to operate all night, the following was established:

- For 5-day charging of storage battery, the total accumulated electrical energy is 1330 Wh (Figure 7); at this time of the year the average value of solar radiation intensity is 418 W/m^2 per day when it is sunny (05.03.2013) and 266 W/m^2 when it is cloudy (08.03.2013) – Figure 6.
- From the measurements of storage battery discharge through street luminaire, two particular points were found:

1) when LED luminaire is switched on, the discharge current is high for one hour – from 6,7 A to 10,3 A (Figure 4) at rated current of the load of 1,5 A (18 W / 12 V_{DC});

2) one hour after switching on the luminaire, the current decreases abruptly and sets up within (3,2 ÷ 3,6) A up to switching off the luminaire.

- The electrical energy consumed by LED luminaire from the morning of 04 March .2013 until the evening of 08 March 2013 is 1100 Wh (Figure 6), taking into account that due to insufficient capacity of storage battery, LED luminaire operates during half of the night hours.

In order to improve the operating modes of PV-LED system, a high capacity storage battery should be selected as well as a solar controller which can rationally set the night operation mode of the luminaire according to the specific time of the year.

4. REFERENCES

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ИСТРАЖИВАЊЕ РЕЖИМА РАДА САМОСТАЛНОГ ФОТОНАПОНСКОГ СИСТЕМА ЗА ВАЊСКО ОСВЈЕТЉЕЊЕ

Сажетак: Снабдијевање уличне расвјете фотонапонском енергијом посљедњих година доживљава брз развој. На Техничком универзитету у Габрову израђен је самостални фотонапонски (ФН) систем који снабдијева ЛЕД уличну расвјету. ФН-ЛЕД систем се састоји од ФН модула, акумулатора, соларног контролера, ЛЕД лампе и система за даљинску визуализацију режима рада. Изучавани су радни процеси за оптимизацију ноћног режима рада. Приказани су подаци о електричној енергији која је складиштена у акумулатору и која се троши за расвјету.

Кључне ријечи: ФН-ЛЕД систем, даљинска визуализација, оптимизација, радни режими, експериментална испитивања, електрична струја.