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AUTONOMOUS PHOTOVOLTAIC LIGHT-SIGNAL UNITS WITH BATTERIES: DEVELOPMENT AND FIELD TEST RESULTS IN THE MOSCOW REGION

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ABSTRACT

Photovoltaic systems are widely used for autonomous power supply in different branches of industry. In many countries, they are applied mostly for road, park and yard lighting and for signal lighting (road sign, traffic light). Some aspects of autonomous photovoltaic power application, concerned with the application of different types of battery are investigated under conditions typical for the Moscow region. Lithium-ion batteries are increasing storage capacity technology for different niches, including stationary, portable and electric transport. Lead-acid batteries are the traditional solution for back-up power and photovoltaic systems.

The storage unit usually has a significant influence on photovoltaic system costs and operational parameters. The possibility of decreasing capital costs and increasing the life cycle of photovoltaic autonomous systems due to lithium iron phosphate-based batteries is presented in this study.

Keywords: photovoltaic system, autonomous power supply, solar power units, lithium-ion battery

1. INTRODUCTION

Rapid development in renewable energy technologies [1] and primarily photovoltaic technologies has ensured the wide application of autonomous solar power units, usually with electrochemical battery energy storage, for light and road traffic control applications. One can see such power units on many roads all over the world. Many companies introduced into the market different versions of such power units and their components. In different regions of Russia, an interest in such solar power applications can be observed. For example in Moscow, several thousands of solar-powered signal-light units have been mounted on pedestrian crossings [2].

A typical solar-powered signal-light unit includes a photovoltaic module, a charge controller, a lead-acid battery (gel or absorbed glass mat type) and light emission diode backlight [3]. Cheapest samples use pulse-width modulation charge controller without maximum power point tracking. Sometimes a small wind turbine is also included as a part of the system [4]. The widest application such units has been seen in China and Germany. Due to their low cost, Chinese systems are actively spreading all over the world. Considering their construction features, all power units can be divided into two types: the first is the block-type, where the photovoltaic module covers the top part of the container and the light-diode unit is situated on its lower part. A charge controller and battery are placed inside the container, which itself is put on the mast. Another design can be characterized as set-type – a set of components (usually the photovoltaic module, light-diode unit and container with a charge controller and battery) each of which is mounted on a mast separately. The tilt angle of the solar panel is defined by the mounting construction.

It is worth mentioning that most of the units imported to Russia are designed for application in southern regions. Attempts to operate them

Table 1. Basic parameters of modern lithium-ion batteries [9]

	$LiCoO_2$|LiC_6	$LiFePO_4$|LiC_6	$LiMn_2O_4$|LiC_6	$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$| $Li_4Ti_5O_{12}$
Specific energy capacity, Wh/kg	180	70–150	120–150	70–90
Cost, USD/Wh	≥3	0,7–1,2	≥1	≥3
Recommended depth of discharge,%	60	70	80	90
Cycle life, cycles	800	3000–5000	1500	≥6000
Operation cell voltage, V	4,2	3,3	3,7	2,1

Fig.1. Solar-powered autonomous signal-light unit

in regions at high and average latitudes, usually lead to failure in autumn and winter. In Fig.1, the first solar-powered light-signal unit mounted in Moscow in 2011–12 is shown [5]. Most of these systems were out of operation during the winter due to low photovoltaic power and a low tilt angle.

The second generation of solar-powered units in the Moscow region was characterised by an increase in photovoltaic module power (from 40–60 W up to 100–120 W) and a tilt angle closer to 90°. But the battery for electric energy storage was left as quite small due to its capital costs.

Photovoltaic power is used to feed the diode light unit and charge the battery during the day. At night, the light-signal unit is fed only from battery. The traditional type of battery used is lead-acid; lithium-ion and nickel-cadmium batteries are used much less often [6]. Lead-acid technology had a series of significant improvements, including the introduction of adsorbed in glass matrix electrolyte, tubular electrodes, special additives to the electrode material, increasing its lifetime. These measures slightly increased the depth of discharge and life cycle of lead-acid batteries. Another advantage of these batteries is their relatively low cost, but not for high-resource deep-cycle batteries with tubular electrodes [7].

Lithium-ion batteries have a longer life cycle and a greater depth of discharge than lead acid technology. In addition, they have better specific energy capacity that allows having less mass and volume of battery for thermal management in wintertime. But higher costs for lithium-ion batteries decrease their competitiveness against lead-acid technology in stationary applications. Another issue of lithium-ion battery applications is the need for a battery management system, which controls voltage and temperature on each cell in the battery and reacts on dangerous fluctuations, increasing battery lifetime, safety and costs [8].

Changes to the battery operational parameters at low environmental temperatures are the special problems. Some of lithium-ion systems as $Li_4Ti_5O_{12}$-based anode are more prone to low temperatures than lead-acid. This is very important for small-scale units (road signs, signal buoys, illuminating devices) where there is a lack of energy for battery container thermal management.

2. CALCULATION AND ANALITICAL STUDIES

Lithium-ion batteries, as well as lead acid ones, have different sub-types of technology, which is concerned with cathode and less anode material influence. Lithium cobalt, manganese oxides, mixed lithium oxides of cobalt, nickel, manga-

Table 2. Solar-powered signal-light unit optimal configurations

Battery type	Photovoltaic module		Battery					
	Area, m^2	Efficien-cy,%	Efficient energy ca-pacity*, kWh	Nominal energy capacity, kWh	Efficien-cy,%	Minimal charge time**, h	Minimal discharge time **, h	Depth of dis-charge,%
Pb-Acid (AGM)	0,98	14,3	6,41	21	83	42,8	35,6	30
$LiFePO_4$	0,98	14,3	6,41	9	84	42,4	35,6	70

* considering recommended depth of discharge, ** considering maximum power flow through charge controller of 180 W

nese, aluminium and lithium iron phosphate are the main cathode materials for a lithium ion battery. Usually lithium graphite is used as an anode material, but several companies produce cells with $Li_4Ti_5O_{12}$-based anode, increasing the cost and cycle life and losing specific energy capacity. The main parameters of modern lithium-ion batteries are given in Table 1.

An energy balance calculation to evaluate autonomous solar-powered light-signal unit optimal configuration for conditions in the Moscow region was carried out.

NASA SSE monthly averaged solar radiation data was taken to estimate photovoltaic module productivity due to its availability and the possibility to obtain climate data for most parts of the Earth [10, 11, 12]. The relative error of solar radiation data is estimated as (10–15) % [11]. The energy balance calculation approach for different equipment configurations was close to that described in [13].

Two types of batteries were taken under consideration: lead-acid (absorbed glass mat type) and lithium-ion (lithium iron-phosphate cathode material), as the most cheap and widespread storage systems for the chosen battery technologies. EPSOLAR Tracer MPPT 1210 charge controller with maximum power point tracking was chosen for the lead-acid version of the solar-powered unit. Its main advantages are its low cost and the possibility to control the electric load (for example load can be fed not only the whole day and night, but also only in selected hours) [15]. Lithium iron-phosphate batteries were purchased from Winston Battery [16] as inexpensive version of lithium ion system, operational in a wide range of environment temperatures. Multi-crystal silicon photovoltaic modules TSM 140 (140 W peak power, JSC Telecom-STV, Zelenograd) were used in both configurations. For the lithium iron-phosphate battery, parameters of the EPSOLAR Tracer MPPT 1210 were chosen for calculation only, later an original controller was developed. A road sign “Crosswalk” with light-emission diode backlight 4 W was fed from the photovoltaic module and battery. Backlight was suggested to operate 24 hours per day during the whole year.

In the given conditions, the energy balance between generation, storage and consumption was estimated for different solar panel power and storage capacities. The optimisation criteria was minimum unit cost at backlight guaranteed operation during the whole year in the Moscow region. Calculated optimal configurations are shown in Table 2.

The guaranteed operational degree for such a unit was defined as the ratio of operated hours in the year to 8760 hours (the whole year).

For the configurations given in Table 2, guaranteed operational degree was about (97–98) % (operation of no less than 8500 h per year). The longest periods when the unit was out of operation in Moscow conditions were in January

3. EXPERIMENTAL APPLICATION

The main challenges for lithium-ion batteries in photovoltaic-based applications are:

– Development of a charge controller which are suitable for lithium-ion battery range of operational currents and voltages;

– Development of battery management system for the lithium-ion battery.

The first problem is concerned with the performance curve of the photovoltaic module. Having

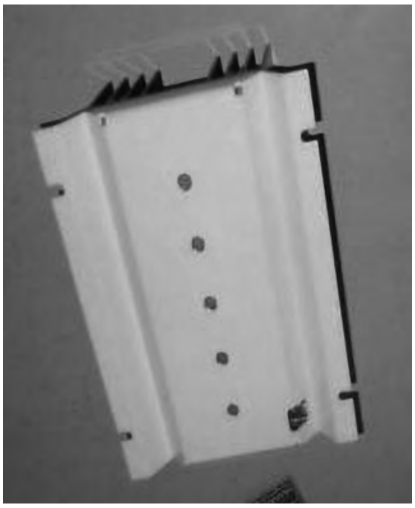

Fig. 2. Experimental charge controller for a lithium-ion battery

deeply discharged battery as a load, the photovoltaic module will be under current close to short circuit which leads to low voltage and efficiency. High current can also be also harmful for the battery, leading to decreased lifetime and possible overvoltage. So charge control is needed with current limitation and maximum power tracking for the solar panel to increase the charge process efficiency. Most of the charge controllers available on the market are adopted for operation with lead-acid batteries

Therefore, at the Joint Institute for High Temperatures a special charge controller for lithium-ion battery has been developed, Fig. 2. It is equipped with a battery management system of passive type to prevent battery overvoltage and maximum power point tracking using a P&O (perturb and observe) algorithm – the current from the photovoltaic module increases while the power increases or battery voltage reaches its upper limit. In case of a power drop after the current increases, the charge controller decreases the current. Current perturbations are generated every 3–5 minutes (due to slow solar radiation change dynamic)

Two solar-powered light-signal units were assembled according to the configuration presented in Table 2, and tested in the Joint Institute for High Temperatures, Fig. 3. Containers with lead-acid (a) and lithium-ion (b) batteries internal view is presented in Fig. 4. Both systems were tested from March to December 2016. Measurement system for data collection on currents and voltages in solar panel, battery and load circuits was built on OWEN data acquisition units. Data acquisition was carried

Fig.3. Experimental solar-powered light-signal units.

Fig.4. Internal view of battery container for lead-acid (a) and lithium-ion (b) batteries

out with a frequency of 0.2 Hz. Data obtained allowed to calculate the energy produced by the photovoltaic module, Fig. 5, stored in batteries and fed to the load. Zero voltage in the load circuit meant non-operational periods of the light-signal unit, so the sum of such periods allowed calculating the operational time during the whole test period and deriving a guaranteed operation degree.

During the whole test period, guaranteed operation degree of 89 % for lead-acid and 87 % for lithium-ion battery equipped solar powered units was obtained. The increased value of guaranteed operation degree was reached due to deep battery discharge – to 80 % instead of 30–40 %. A commercial charge controller only monitors voltage change in a battery, but for high capacity battery discharging by small current, voltage change is quite slow and does not represent correctly the depth of discharge. The developed controller also uses voltage as a control parameter, but the threshold voltage for load disconnect was preliminarily defined during tests on characteristic for photovoltaic applications of low currents. Greater depth of discharge leads to accelerated battery degradation.

Table 3. Capital costs and their structure for autonomous solar-powered light-signal units

Battery type	Capital costs		
	Components	**Costs, rub**	**Share,%**
Version A. Lead-acid battery (AGM)	Solar panel	7600	6,3
	Mounting construction	2800	2,3
	Charge controller	4500	3,7
	Battery	72000	60
	Cables, wiring, container	13000	10,7
	Construction works	20000	17
Total (for version A)		120000	100
Version B. Li-ion battery ($LiFePO_4$)	Solar panel	7600	8
	Mounting construction	2800	5
	Charge controller	7300	10,2
	Battery	55440	49
	Cables, wiring, container	12000	10,8
	Construction works	19000	17
Total (for version B)		112500	100

Experimental data deviation from the calculated results can be explained taking into account the shading of photovoltaic modules by nearby buildings in evening, which was not described during calculation.

4. ECONOMIC ESTIMATION

Cost shares for different experimental sample components in both configurations are given in Table 3.

Mass and dimensions estimates for both battery types are given in Table 4.

According to the relatively short lifetime of a lead-acid battery, one should estimate operational expenses which account for battery replacement over a 20 year period (averaged lifetime of modern solar panels). Manpower and transportation costs for battery replacement are estimated as 20 % of battery cost. Exact life cycle estimates at different depths of discharge is problematic, so a rough estimate is made, suggesting that 365 discharges down to recommended depth of discharge occur during the year. The calculation results for operational costs of battery replacement are given in Table 5.

Therefore, application of lithium-ion batteries is more competitive considering the whole period of the solar-powered light-signal unit's operation

5. CONCLUSIONS

1. Application of solar powered light and signal units with a high degree of guaranteed operation under the conditions of Russian regions requires a correct estimation of climate and geography factors. A high degree of guaranteed operation leads to an upscale of battery and solar panel and increased cost of the whole unit.
2. Application of a lithium-ion battery allows to decrease the cost of construction and operation of solar powered autonomous energy units due to its longer cycle life and greater depth of discharge than lead-acid batteries. A battery container can be made much more compact than for lead-acid batteries of the same efficient energy capacity. For today, application of lithium iron phosphate based batteries seems to be the most attractive.
3. For successful integration of li-ion batteries into solar powered systems efficient charge controllers with a solar panel maximum power point tracking algorithm, functions of voltage at each cell

Table 4. Battery type mass and dimensions estimates

Battery type	Mass, kg	Volume, m^3	Efficient energy capacity, W·h	Nominal energy capacity, W·h
Version A. Lead-acid battery (AGM)	855	0,8	6410	21367
Version B. Li-ion battery ($LiFePO_4$)	153	0,12	6410	9157

Table 5. Expenses for battery replacement for 20 years

Battery type	Capital costs, thousands of rub	Battery replacement for 20 years	Total costs over 20 years, thousands of rub
Version A. Lead-acid battery (AGM)	120	6	504
Version B. Li-ion battery ($LiFePO_4$)	112,5	2	230

of the battery and the battery depth of discharge, adequate controls must be applied.

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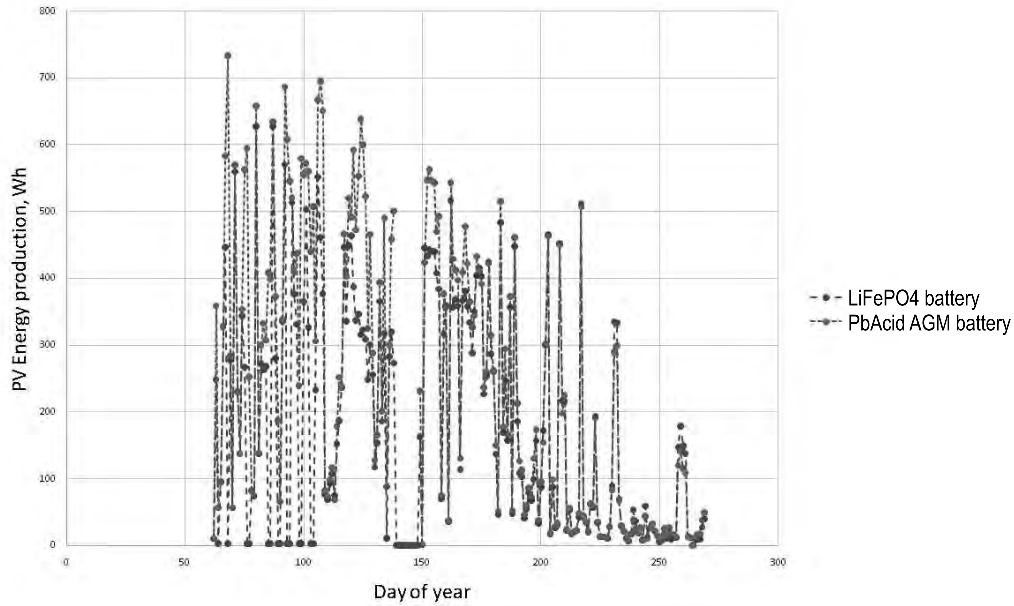

Fig. 5. Solar panel energy production for both experimental samples in 2016, March-December

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