ISOLATED SOLAR POWER STATION

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Abstract. The paper describes a design of a simple small solar photovoltaic energy system that has been realized for electric power supply of objects situated on a (far-away) remote site out of reach of the power line system. Output of this power system is designed in order to supply a week-end operation of a shooting range for a hunting association and an amateur transmitting station. This system delivers approximately 5 kWh during Saturday and Sunday, in months with minimum sunshine (since November to February) and up to 10 kWh in months with higher level of sunshine. The construction of the system is optimised regarding maximal reliability, service unpretentiousness and minimal purchase costs.

Keywords: solar power station, $LiFePO_4$ accumulator, balancer, battery management system.

Introduction

The isolated solar power station is designed to ensure the operation of an amateur radio station and other facilities in a remote location at weekends. Energy demandingness of the device is approximately 10 kWh. The system is composed of two parts: a photovoltaic system generating electric energy at the time of sunlight, and an accumulator system accumulating the energy to be available when the photovoltaic panels do not supply any electric power [1]. The accumulator capacity is therefore chosen to allow the accumulator to keep the required 10 kWh.

The design and construction of a small photovoltaic system is described. The construction is easily manageable because the components are cheap and available.

Materials and methods

The construction of the solar power system is based on the average solar radiation on a horizontal surface (E, kWh·m^{-2}) in the Czech Republic during the year, see Table 1 [2].

Table 1

Average solar radiation in CR

Month	1	2	3	4	5	6	7	8	9	10	11	12
***E* (kWh·m^{-2})**	20	30	60	100	140	150	150	140	110	70	30	20

The photovoltaic system is designed to supply the accumulator with energy in the period of more intensive sunshine (March-October) within one week, and in the period of less sunshine (November-February) within two weeks.

The most common photovoltaic panel with efficiency 15-17 % and 35º tilt can obtain the same amount of electric energy which can be nominally compared with the energy from the panels with a peak output of 0.9-1 kW and a surface area of approximately 6 m^2 [3]. Coincidentally, the system of such proportions will supply 15 kWh on average, during one week in summer or two weeks in winter, which safely ensures charging the accumulators. The price of panels, including their installation, will be around 1,000 EUR.

Significantly more difficult it is to design and construct the accumulator system itself. The accumulator with a capacity of 10 kWh is relatively large, and thus it must be assembled from individual cells or smaller accumulators available on the market. Firstly, it is necessary to choose appropriate electrical and economic parameters of the system. This means to choose between NiCd accumulators, or $LiFePO_4$ and Pb accumulators which are widely available on the market offered by several manufacturers. The comparison of the accumulator system parameters is shown in Table 2 [4].

NiCd accumulators are significantly the most expensive of all. Their usage is acceptable only in specific operational conditions, e.g., deep discharging, very low operating temperatures or overcharging, whereat other batteries could be destroyed very fast.

At $LiFePO_4$ and Pb accumulators, the decision-making will be influenced by their specific properties, see Table 2. The usage of Pb accumulators is limited by their heavy weight, large dimensions and capacity drop at high discharge current, e.g., the ratio between two-hour and ten-hour capacities is approx. 70 %. Using $LiFePO_4$ accumulators is complicated by the necessity of the continuous monitoring of their operating parameters, as overcharging or discharging under the minimum voltage quickly destroys them.

Table 2

Standard accumulator system parameters

Accumulator system	Ni-Cd	$LiFePO_4$	Pb (6 V battery)
Energy density, $Wh\cdot kg^{-1}$	45 to 80	90 to 120	30 to 50
Cycle life at 50 % DOD	1500	5000	1600
Planned system lifespan, years	5	10	10
Self-discharge rate, % per month, for 20 ºC	20	5-10	5
Operation voltage, V	1.2	3.2	2
Discharge current max-opt, A/Ah	20C/1C	25C/5C	5C/0,2C
Operation temperature, ºC	-40 to +60	-20 to +60	-20 to +60
Cycle effectivity, %	65 to 85	85 to 95	60 to 90
Cell capacity, Ah	320	300	300
Cell price, EUR	320	400	240
Total operational costs for 1 kWh, EUR	1	0.16	0.16

Yet, $LiFePO_4$ accumulators have been selected for the presented system because of their robustness and negligible efficiency drop at a high discharging current, and high ampere-hour efficiency at a low charging current.

Typical voltage characteristics during charging and discharging $LiFePO_4$ accumulator are shown in Fig 1.

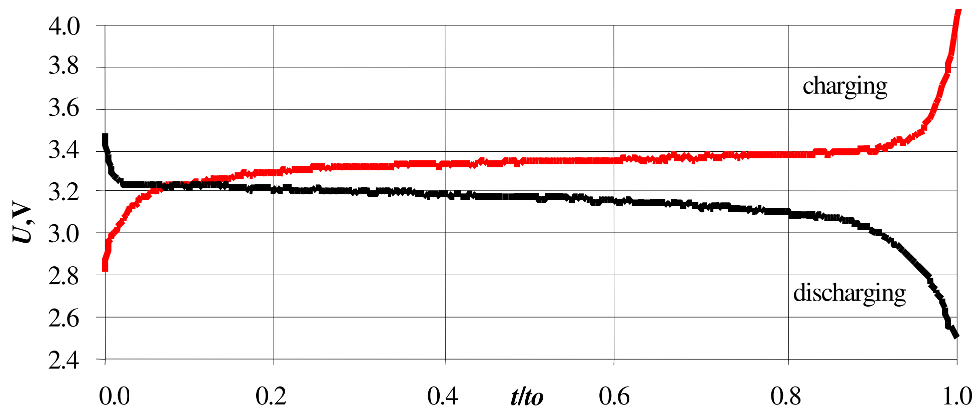


Fig. 1. **$LiFePO_4$ accumulator charge/discharge curve**

At the beginning of the discharging process, the cell voltage reaches approximately 3.5V. Then it decreases rapidly to the level of approx. 3.2 V and further remains stable up to about 90 % of the discharge (3 V). During discharging, the cells have also very low internal impedance, which always depends both on the monitored frequency and the level of the cell charging. The absolute value of internal impedance is inversely proportional to their capacities and at standard cells it can be expressed by an empirical equation (1)

$$|Z|(\mathrm{m\Omega}) = \frac{100 \div 300(\mathrm{Ah})}{Q} \tag{1}$$

During the charging process, an initiative cell voltage is by 0.1-0.2 V higher than that on which it was discharged. Then the voltage quickly rises to a level of approx. 3.3 V and remains stable up to about 90 % of the charge, where the cell voltage is 3.4V. Then, the voltage rises quickly to the level of 4 V when the cell is fully charged.

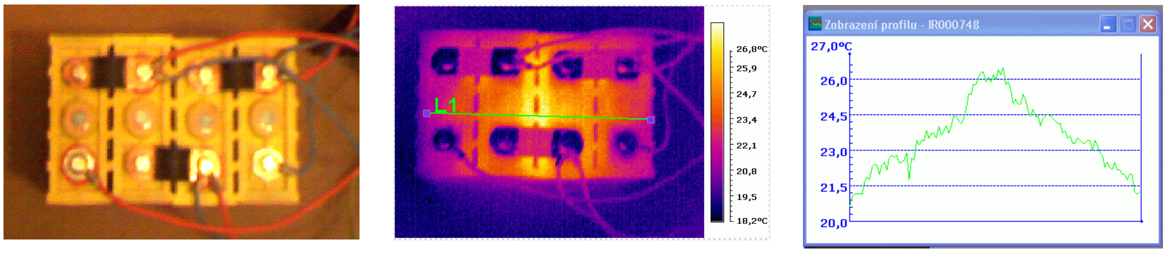
These characteristics are usually considered as marginal, physically possible states. Operation parameters and recommended parameters which should satisfy the operating mode are defined in narrower limits. The fact that each producer and author indicates slightly different values [5-7] can bring about some complications. Only some technical documents mention the influence of the operational parameters on the lifetime of the cells. Several examples are given in Table 3.

Table 3

$LiFePO_4$ accumulator parameters

Manufacturer	Winston Battery	Thunder Sky	Sinopoly	PowerStream
Minimal discharge voltage, V	2.8	2.5	2.65	2
Maximal charge voltage, V	3.8 to 4	4.25	3.65 to 3.7	3,65 to 4.2
Operating temperature range, °C	-40 to +85	-40 to +85	-20 to +55	-10 to +60
Charge operating temperaure, °C	-40 to +85	-40 to +85	-	0 to +40
Constant discharge current, A/Ah	3C	3C	3C	2C
Standard discharge current, A/Ah	0.5C	0.5C	0.3C	0.2C

Some manufacturers and authors accentuate also the monitoring of temperature during the accumulator charging and a charge control according to the actual cell temperature. In the presented system, where the cells are charged at less than 0.1 C, as experimentally verified, it is not necessary to solve these problems. The test results are shown in Fig. 2. Four tightly arranged WB-LYP40AHA cells were charged for 4 hours by 10 A current. They are presented in the form of an IR range image, temperature profile and the image in the visible range. The temperature of internal cells, the cooling of which is worse, is approximately about 5 °C above the ambient temperature. But it does not noticeably affect the functioning of the cells.

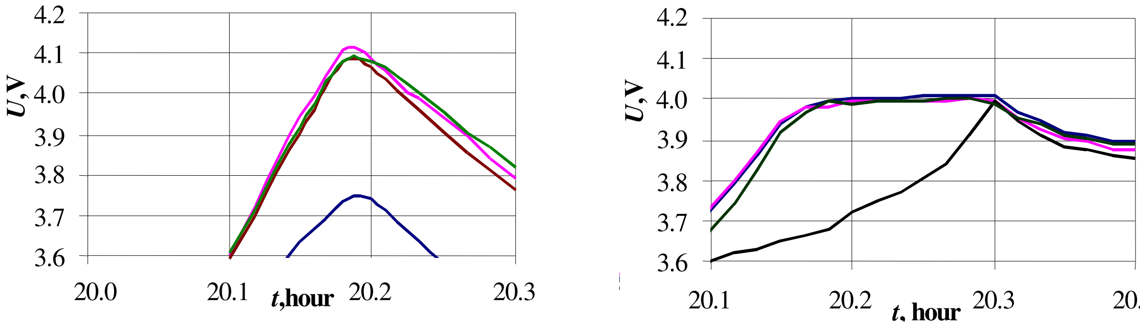


a) b) c)

Fig. 2. **Temperature field on the accumulator:** a) photo; b) IR imag; c) temperature profile

If the accumulator is connected in series, effective management of its operation based on the total voltage of the accumulator could be possible on condition that the cells were absolutely identical. Then the total voltage would correspond to the multiple of the voltage at each cell, and all the cells would be directed to achieve the same parameters.

In practice, the cell with the smallest capacity is charged as the first and discharged as the first, and soon after its threshold limit values of both charge and discharge voltages are exceeded and consequently the cell being continuously operated is very quickly destroyed. Similarly, its lower charge efficiency appears. The cell, if not fully charged in later charging, is discharged earlier, and the whole process results in a deep cell discharge.



a) b)

Fig. 3. **Voltages of four cells at the end of the charge cycle:** a) without balancer; b) with balancer

Fig. 3, a displays the time dependence of the voltages of four cells at the end of the charge cycle. The charge cycle is finished if total voltage reaches 16 V. The voltages of three cells are almost identical; the fourth cell has lower clamp voltage, and thus it is charged later than the other ones. However, it will not be charged, because the voltages on other cells will rise rapidly to the levels of about 4.1 V, and the total voltage of the accumulator reaches 16 V and the process of charging is finished.

A similar process during the cycle charge and discharge is illustrated for two cells in Fig. 4

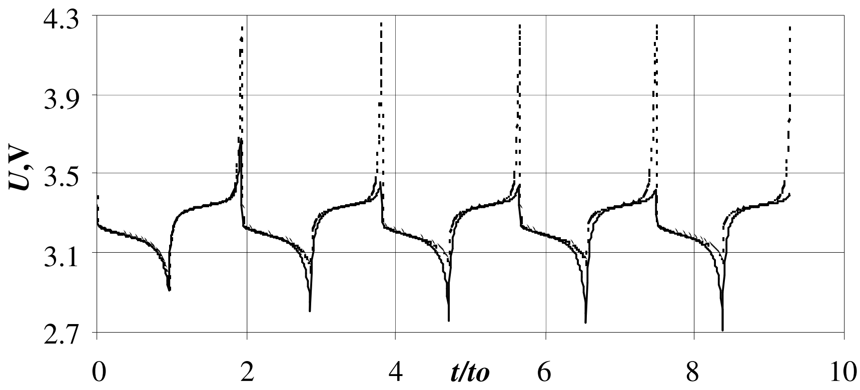


Fig. 4. **Charge/discharge waveform of two cells**

The process is based on the assumption that the two cells are charged and discharged with a constant current which corresponds to the charge and discharge of the first cell at a time t_0 (indicated by a dashed line). The second cell has 90 % capacity of the first cell. The accumulator is controlled by the total voltage and by minimum and maximum voltages on each cell. At the beginning of the displayed waveform, both cells are fully charged, the process of discharging finishes when the total voltage drop falls to 5.8V, and after a short break (0.2 hours) the process of charging starts. Charging ends when the cell voltage reaches 8 V, respectively increase in cell voltage of 4.25 V, and after a short break (0.2 hours) starts discharging. In other charge cycles, charging is finished when the voltage on the first cell increases to 4.25 V, and the second cell with lower capacity is not fully charged. The second cell is in each cycle discharged to a lower voltage than that on the first cell, and with respect to the charge termination by the voltage on the first cell, it is less charged. The total available cell capacity gradually decreases in cycles and is slightly lower than the capacity of the second cell. Cell voltage levels periodically move away from each other, and if the termination of the maximum charge voltage is not at least ensured, the first (the better) cell will be overcharged.

Multi-cell accumulator cannot operate effectively in this way. The solution lies in balancing the cells in the accumulator. Each cell is parallel connected to an electronic circuit. If the clamp voltage on the cell reaches the desired value during the process of charging, the circuit removes a charge current from the cell and the clamp voltage is stabilized on a pre-set value. Some active balancers can work as bidirectional during discharging. At deep discharge of any individual cell, the balancer feeds the power to its terminals from the entire battery power. The change in charging at the end of the charge cycle using the balancer with an operating voltage of 4V is shown in Fig. 3, b. The limitation of the maximum cell voltage to 4 V, longer charging by about 0.15 hour, and thus the desired charge of the fourth cell up to the voltage of 4 V is evident.

Results and discussion

The system design is optimized to maximum reliability, ease of operation and minimal cost. To reach maximum reliability of the whole system, it is necessary to use a minimum number of components, since the reliability of the overall system is dependent on the multiple of reliability of individual components.

Power circuits are therefore designed so as to ensure minimal complexity of the system. Therefore it is completely inadvisable to use dozens of switching converters which might be supposed to contribute to a potential increase in efficiency of the system by a few percent. Even if the switching converters were used, they should be perfectly protected against EMI noise because in its vicinity there is a device receiving radio signals on the level of cosmic noise. Both the solar generator and accumulator are designed to match, and thus they are connected directly without a DC converter.

The balancer balancing accumulator cells is passive. At supposing maximal cell capacity deviations up to 10 % of capacity of the best cell, active balancing system, which is much more complicated and less reliable, would increase the effectiveness of charging by these 10 % at maximum.

For accumulator management an analogue HW system is used. The evaluation of the required limiting actual values is performed by simple analogue comparators the output signal of which is processed by conventional combinatory circuits. A microcomputer, which is currently offered on the market [8], is not recommended to use for battery management, as it is less reliable when compared to the simpler analogue system. Furthermore, the fact that its activity can be influenced by accidental or atmospheric interference even after they were resolved further reduces its reliability in operation.

A schematic block diagram of the system is shown in Fig. 5. An energy source is a solar generator. It was assembled of 9 pieces of 100 W panels available on the market, regarding the required voltage and power parameters, with an output characteristic as shown in Fig. 6. The panels are connected in three parallel branches having three panels in series. Regarding the necessity to protect the solar generator against damage, the panels are placed on a pole at a height of 3-6 meters above the ground. They are located in cases made from perforated sheet metal and wire mesh to protect their front and rear sides against falling objects [9], see Fig. 7.

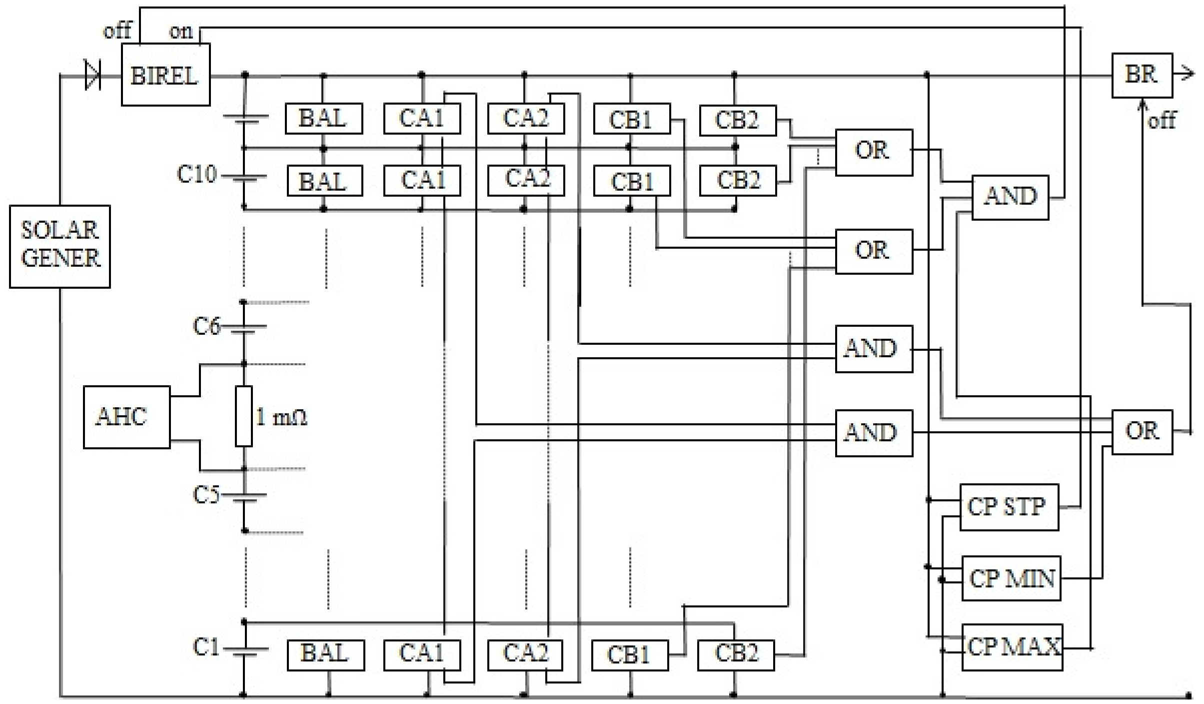


Fig. 5. **Schematic block diagram of the system:** AHC – amper hour counter; BAL **–** balancer; BIREL – bistable relays; BR – breaker; C*i* (*i* = 1 up to 11) cells; CA1, CA2 – minimal cell voltage sensors; CB1, CB2 – maximal cell voltage sensors; CP STP – comparator stop; CP MIN – comparator minimum; CP MAX – comparator maximum; SOLAR GENER – solar generator

The accumulator is connected to the solar generator directly by a buffer diode and bistable relay. A diode prevents a reverse current to flow and the bistable relay switches the charge circuit at an accumulator voltage 35 V and switches it off at a voltage 43 V. The accumulator is composed of eleven WB- LYP300AHA cells connected in series. The cells are connected in two groups formed by 5 and 6 cells. A current sensor shunt at/in an ampere-hour counter is placed between them. Such design enables supplying operational amplifiers of an ampere-hour counter with accumulator voltage without using converters or level shift circuits.

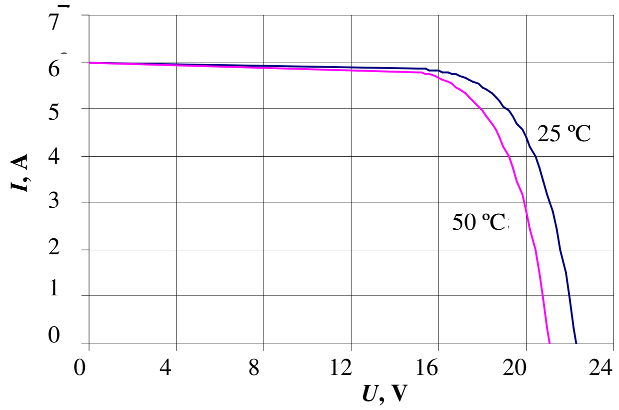


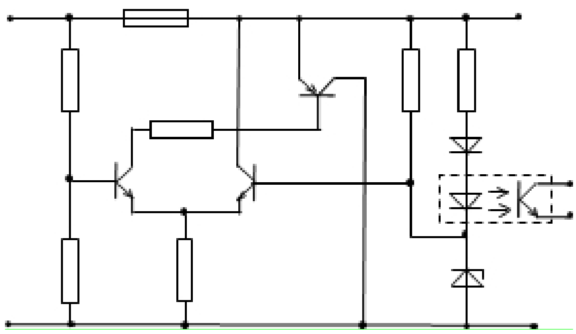
Fig. 6. **Output characteristic of photovoltaic module** Fig. 7. **Photovoltaic module mounting**

The counter works as a double integral voltage/frequency converter. It registers the charge during charging and discharging by an up-down counter. The balancer BAL and comparators CA1 CA2, CB1 CB2 are parallel connected to each cell to indicate the minimum and maximum cell voltage.

The balancer is designed as a high-power shunt voltage stabilizer. It is realized as a special circuit composed of discrete components to be supplied only from the cell to which it is connected. It is necessary not to be discharged by the balancer if the cell is not charged.

The balancer control amplifier is designed as a differential amplifier with a dual transistor. It compares both the reference voltage of 1.2 V and a sample balancer clamp voltage. The amplifier output signal controls a bipolar power Darlington transistor which acts as a controlled high-power load. The balancer is further complemented by an element voltage indicator, the function of which will be discussed below.

A simple circuit with a single high-power transistor can be used for the currents of 10 A at maximum. For higher currents, several identical balancers are connected in parallel. A volt-ampere characteristic of the applied balancer used is shown in Fig. 8.



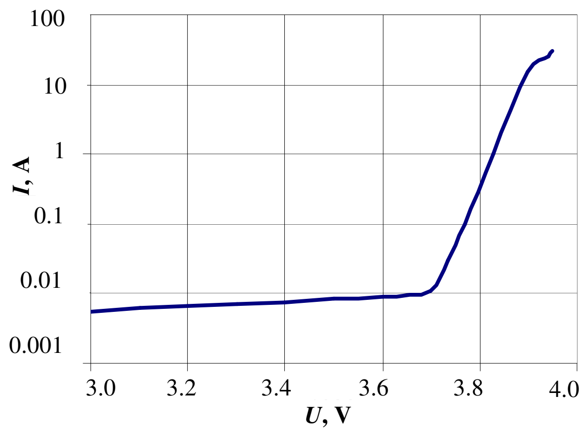


Fig. 8. **Circuit diagram of the balancer and its volt -ampere characteristic**

The comparators used for the indication of the cell voltage are all designed in the same way using an optocoupler which separates the input voltage and output current circuits. The comparators act as a voltage/current converters. The output current is indicated by the voltage drop at the load resistor which is analyzed by another voltage comparator galvanically separated from the optocoupler input circuit. Block circuit diagram of the comparator is shown in Fig. 9.

A typical dependence of the output current of the optoelectronic converter on the input voltage is shown in Fig.10. A suitable choice of an operating current and impedance in the input optocoupler circuit minimizes its temperature dependence so that the error in the indication of the selected cell voltage values in the temperature range 0-40 ºC is less than ± 1 %. The converter output current is not so much influenced by the output port voltage. In the description of the cascaded two-port, the influence of the output voltage on the output current is characterized by the voltage no-load transmission size from 0.001 to 0.002. This allows realization of logical functions for controlling the accumulator by a series connection of the converter outputs. The connection causes negligible errors of several tenths per cent in evaluating the cell voltage.

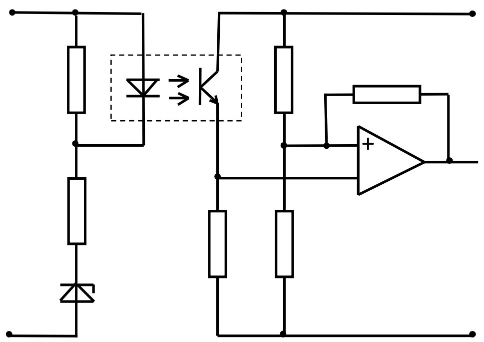


Fig. 9. **Circuit diagram of the comparator**

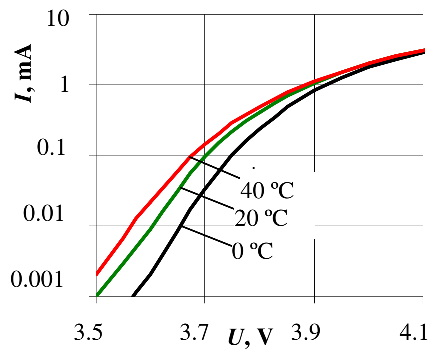


Fig. 10. **V/A characteristics of the optoelectronic converter**

AND circuits are realized by comparators, see Fig. 9. Instead of one phototransistor from one optoelectronic transducer, a chain of eleven transducers is connected in series. When the voltage of any cell drops under the minimum limit (2.8 V), the current in the chain decreases, and the OA comparator switches to the output level HI.

OR circuits are also realized by a single OA comparator the input of which (inverting input OZ) is connected to the outputs of individual voltage/current converters through the OR gate diode. If the voltage in any cell exceeds the limit maximum (4 V), an OA comparator input voltage increases, and a comparator output switches to level LO.

The total accumulator voltage is evaluated by three comparators as a minimum discharge voltage (32 V), charge starting voltage (35 V) and final charge voltage (43 V). Comparator hysteresis is set to approx. 0.1 V. If the total value of the voltage reaches 43 V, the comparator of the final charge voltage switches to an output level LO. The output signal together with the output signals of the OR gates, which monitor the voltage of individual cells, are conducted to a NAND gate. The gate output signal switches a bistable relay and charging finishes in case that the total voltage or voltage of any cell exceeds the defined limits.

If the total voltage drops under 32 V, the comparator of the minimum discharge voltage switches to an output level HI. The comparator output signal together with the output signals of the AND gate monitoring the voltages of individual cells are conducted to the OR gate. The gate output signal switches off the circuit breaker of the output power circuit in case the total voltage or voltage of individual cells drops under the defined limits. Indicating and triggering circuits are doubled to ensure maximum charging and minimum discharging voltage better.

If the total voltage drops under 35 V, the comparator of charging initial switches to an output level HI. The output signal of the comparator switches a bistable relay and charging is allowed in case the photovoltaic generator supplies the charging current. Two power inverters of different output voltages and lighting equipment represent a power load of the system. The power inverter 3.2kV/0.8A serves for supplying the main electrical equipment and power inverter 3.2 kV/0.8A feeds a power amplifier of the transmitter. All three power consumers are fed directly from the accumulator voltage of 36 V.

The level of charging in the period from January 1to March 15, 2015 is shown in Fig .11.

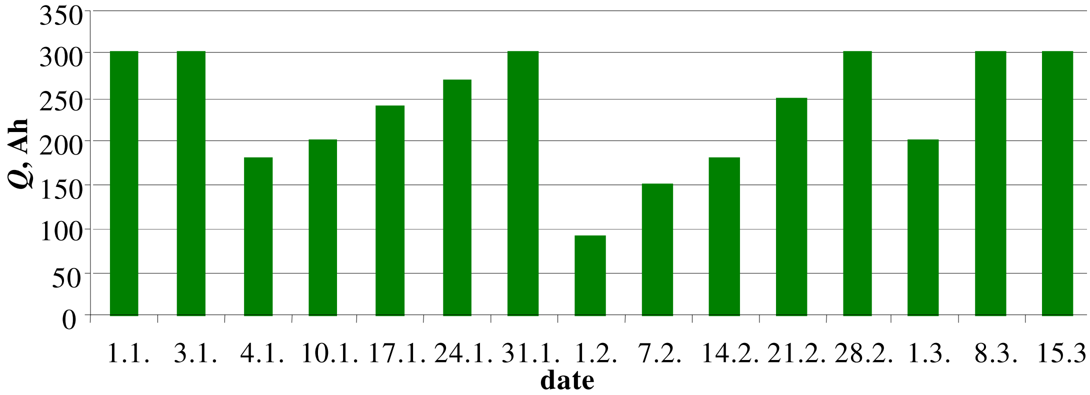


Fig. 11. **Level of accumulator charging**

Conclusions

A solar power station, which in contrast to common commercial arrangement uses LiFePO4 storage batteries, has been implemented. Electronic control system for LiFePO4 storage batteries has been designed and realized. This system scans voltage of each cell and whole accumulator and controls their charging by photovoltaic panels and discharging by loadings according to specified operationally parameters.

The system was put into operation in late 2014. The accumulator was fully charged before the installation. The electric power was consumed in the following days: January 4, February 1 and March 1, 2015. Charging depended on the sunshine intensity and accumulator condition.

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