Effective control and battery charging system of an island PV power plant

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Abstract. The paper presents a new concept of an autonomous PV power plant regulatory system with LiFePO$_4$ batteries, which was functionally verified. The hardware system is significantly simpler and more operationally reliable. It also shows higher efficiency and lower acquisition costs than conventional commercial systems. The proposed control system was optimized for charging a multi-cell battery by PV electric energy. The system automatically maximizes the power supplied by the photovoltaic source and minimizes the power loss caused by balancing the individual cell charging processes. The problem of charge balancing is solved without the balancers. Battery cells are recharged from the separate converters supplying the PV power. The converters are controlled to observe a LiFePO$_4$ battery charging mode while controlling the photovoltaic generator (PVG) load resistance based on an MPP monitoring. PVG power is not supplied to the charged cells, which are in this way protected from overcharging. The entire PVG power is fed to the cells to be charged. The transmission from the converters is controlled in order not to exceed the voltage and current limits at the terminals and to minimize the actual voltage deviation from the control voltage at the PVG output. The control voltage is generated as an MPP voltage approximation according to the load character-istics and the actual PVG operating conditions.

Key words: LiFePO$_4$ battery, autonomous PV power plant regulatory system, MPP tracking.

INTRODUCTION

An autonomous PV power source must be equipped with a battery that is capable of covering the power supply requirements in case the PVG is not sufficiently illuminated. The battery is recharging in case of sufficient PVG irradiation and if its power is greater than the power consumed by the appliances.

Charging the battery by a direct interconnection with the PVG is possible only in special cases, i.e., an optimum working voltage of the photovoltaic generator must be slightly higher than the battery charging voltage. Since the battery cells connected in series will charge unevenly, they must be resistant to overcharge (e.g., NiCd batteries with a liquid elecrolyte).

Therefore, currently used modern systems are designed to maximize the power supplied from the PVG and to prevent overloading the battery cells in a wide range of operating voltages and currents (Glavin & Hurley, 2007; BMS123, 2019). A block diagram of the charge control is shown in Fig. 1.
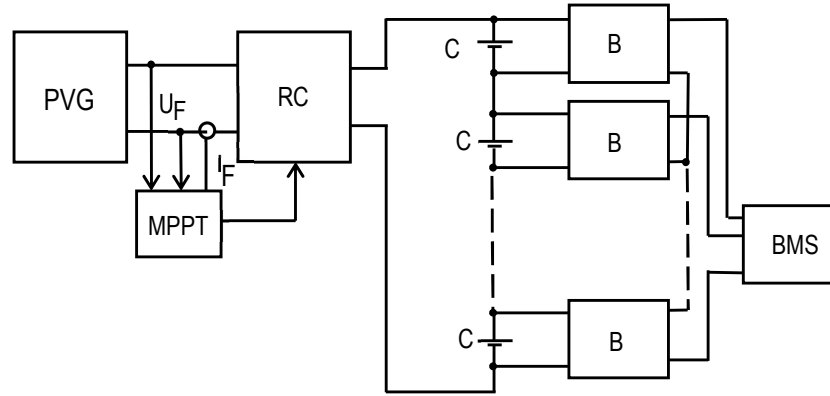

Figure 1. Block diagram of the charge control.

The PVG and C battery cells are interconnected via an regulated converter (RC) that transforms the power supplied from the PVG to its input at a certain voltage. The output power is then consumed at a different voltage, corresponding to the battery charge. Voltage and current levels at a PVG output are controlled by the Maximum Power Point Tracker (MPPT), so that the PVG delivers maximum power under actual operating conditions. The current I_{MP} and voltage U_{MP} corresponding to the MPP, when the PVG supplies the highest electric power, are found on the actual load characteristic, see Fig. 2.
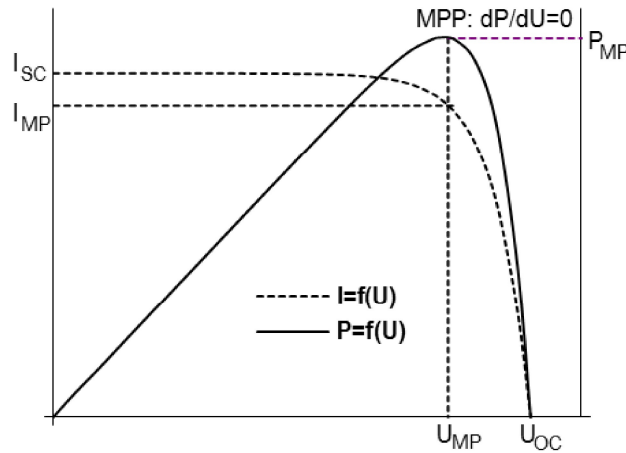

Figure 2. Power and current characteristics of the photovoltaic generator.

If the operating conditions change, the course of the PVG load characteristic changes as well. The current supplied from the PVG is approximately directly proportional to its irradiation. A PVG open-circuit voltage U_{OC} depends decisively on the temperature. As the temperature rises, it decreases by approximately 2.1 mV K^{-1}.

The MPPT is currently implemented as a control computer. Its input parameters are the values of output voltage and PVG current, or other potential values. Its output signal sets the voltage or current transmission of the controllable RC so that the actual values of its input voltage U_C and current I_C are as close as possible to the U_{MP} voltage and current I_{MP} in the maximum PVG power point.

The voltage and current levels in the output circuit of the controllable RC converter are controlled automatically according to the actual charging voltage of the battery so that the converter supplies the required power. Balancers B are connected to the individual cells, which are usually connected to the Battery Management System (BMS), as well. The BMS ensures the compliance with the permissible operating conditions of each battery cell.

MATERIALS AND METHODS

Electrical output power P supplied by the panel can be expressed as (1), (Papez & Papezova, 2016). The point, when the panel supplies a maximum power (P_{MP}) could be determined by finding the function extreme (1) according to Eq. (2).

$$P = UI = \left[\frac{NnkT}{e} \ln \left(\frac{I_{ph} + I_o - I}{I_o} \right) - IR_s \right] I, \tag{1}$$

where I – output current of the solar panel (A); I_{ph} – photovoltaic current of the solar panel (A); I_o – equivalent diode saturation current; R_s – equivalent series resistance of the solar panel (Ω); N – number of cells in series in the solar panel; n – equivalent diode ideality factor; k – Boltzman constant ($k = 1.381 \times 10^{-23}$ J.K^{-1}); e – electronic charge ($e = 1.602 \times 10^{-19}$ C); T – cell temperature (K); U – output voltage of the solar panel (V).

$$\frac{\partial P}{\partial I} = \left[\frac{NnkT}{e} \ln \left(\frac{I_{ph} + I_o - I}{I_o} \right) - IR_s \right] - I \left[R_s + \frac{NnkT}{e(I_{ph} + I_o - I)} \right] = 0. \tag{2}$$

However, Eq. (2) is not suitable to search for MPP, as the equation neglects further dependence of solar panel parameters on the operating conditions that, in practice, significantly influence the MPP position.

Consequently, at present are used the techniques that determine the actual values of the solar panel parameters determining MPP (Abderezak et al., 2018):
A. Numerical calculation of the derivative of the observed power function is the basis of the Perturb and Observe change evaluation method (P&O). Gradually is reached the state in which the calculated derivative value approaches the zero value and which corresponds to the maximum delivered power.
A. The method of Incremental Conductance (INC) is based on a numerical calculation of conductivity and incremental conductivity at PVG terminals that are each other compared. In that way, a state, in which the calculated conductivity and incremental conductivity values are equivalent and which corresponds to the maximum delivered power is gradually found.
B. A constant voltage method (CV) is based on the fact that for standard monocrystalline photovoltaic panels holds the approximate ratio between the voltage at the MPP point and the U_{OC} voltage of the open-circuit photovoltaic panel, which is approximated according to the PVG output voltage if the load is disconnected.

C. A short-current pulse method (SCP) is based on the fact that for standard monocrystalline photovoltaic panels holds the approximate proportion between the current at the MPP point and a short-circuit current of the photovoltaic panel I_{SC}, which is approximately determined according to the PVG output current during a short circuit at its terminals.

The battery management system ensures the balancing of the charging processes of individual battery cells. In practice, if the battery is constructed as an inter-connection of non-identical cells in series, its simple control according to the total battery voltage leads to the cell damage. The lowest-capacity cells are deeply dis-charged. They are not fully charged because the battery charging process is terminated when high capacity cells start to be overcharged. Moreover, in the cyclic operation, insufficiently charged cells discharge more deeply in the succeeding cycles and the differences increase. Similarly, the lower charge efficiency of the cell appears. The cell is later charged, and if it is not fully charged, it is discharged earlier and the whole process leads in a deep discharge of the cell and further decrease in its charge efficiency.

The problem is solved by balancing the cells. An electronic circuit is connected in parallel to each cell. If the terminal voltage of the cell reaches the selected value during charging, the circuit consumes the charging current from the cell and stabilizes the terminal voltage at the selected value. Battery charging is complete when the voltage of all cells reaches this selected value and all cells are fully charged.

Balancers are, in the simplest case, passive voltage stabilizers with a I-V characteristic of an ideal Zener diode with a knee voltage corresponding to the voltage of a fully charged cell. At this voltage, after charging the cell, the balancer consumes the charging current, i.e., it prevents the cell from overcharging and dissipates the power.

The maximum dissipated power of the balancer must correspond to the maximum charging power that can be supplied to the cell. The maximum dissipated power of all balancers must correspond to the maximum power that can be supplied to the battery terminals.

When charging the last cell of the battery with *n* unequal discharged cells, the balancers dissipate *(n-1)/n* of the input power.

Significant decrease of power dissipation can be achieved by using active balancers. Active balancers are controllable bi-directional converters allowing draining the charging power from the cell terminals to the auxiliary bus after full charging. In case the electrical power is available on the auxiliary bus, it is distributed by other active balancers to the terminals of so far uncharged cells. In principle, the whole supplied power can be losslessly utilized during the entire charging process, and the battery can be charged in a shorter time.

The disadvantage of the described BMS in photovoltaic systems is their considerable HW and SW complexity. In the systems with passive balancers, complications lie also in their cooling, as their waste heat may cause a significant battery overheating.

In active balancing systems is used a DC/DC PWM converter chain, whose maximum transmitting power is greater than the double of the maximum PVG power. This makes the construction of the charging system more expensive and reduces its reliability. Computer-controlled systems can be very unreliable due to a complicated SW and possible malware attack, particularly if they are connected to a PC and allow a remote administration via the Internet.

DESIGN AND IMPLEMENTATION OF THE SYSTEM

The new control system uses separate converters for the power transmission from a photovoltaic generator to individual cells. They simultaneously provide both charge power transmission and cell balancing during charging. The block diagram of the system is shown in Fig. 3. The input ports of the converters are connected in parallel and are supplied from the PVG output. As to the load optimization of the PVG, all converters are controlled according to the control voltage. It approximates the voltage U_{MP}, which is generated by a special circuit according to the temperature of PVG panels and their irradiation following the Model-based MPPT algorithms. (Hohm & Ropp, 2003).
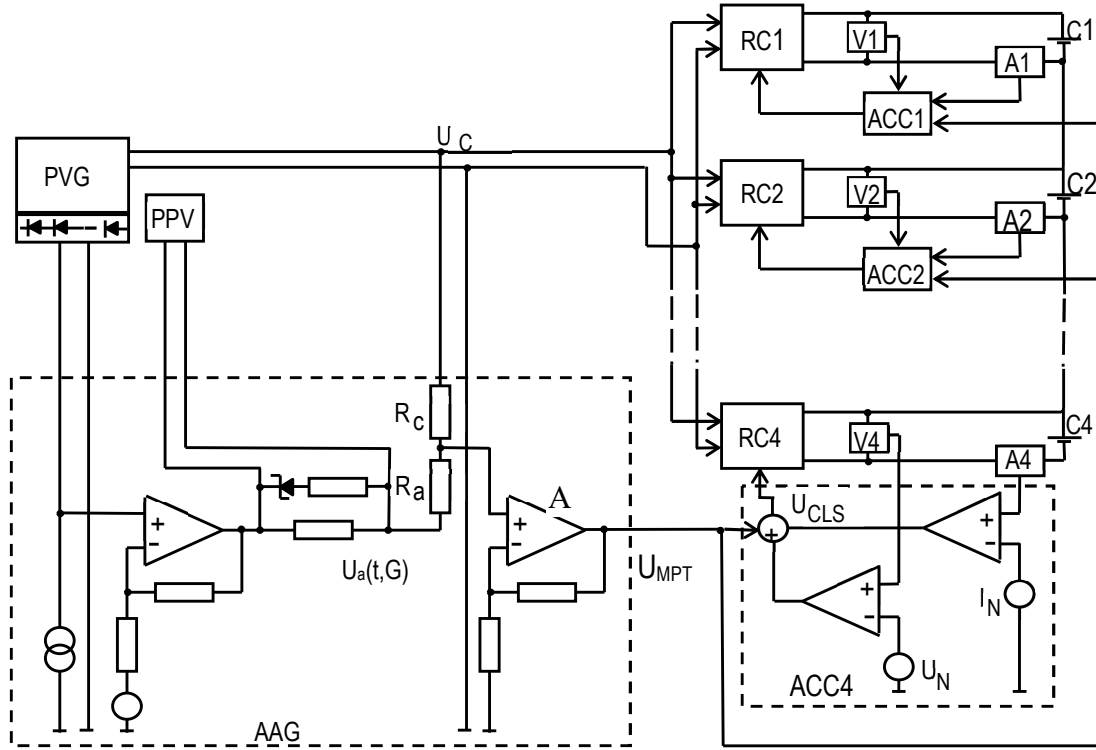

Figure 3. The block diagram of the realised system.

The control of the individual converters is further corrected according to the charging voltage and current of the connected cell such that the terminal cell voltage does not exceed the level corresponding to the full charge and that the maximum selected charging current is not exceeded.

The control is based on an analogue principle with analogue control signals and on the basis of physical principles in a controlled device without their digital simulation.

The system depicted in Fig. 3 comprises a PV generator (PVG) and a recharge-able battery consisting of three cells C1, C2, C3, C4. Each cell of the charged battery has its own control converter RC1, RC2, RC3, RC4, whose power inputs are interconnected in parallel and connected to the PVG output. The power outputs of the control converters are connected via voltage sensors V1, V2, V3, V4 and current sensors A1, A2, A3, A4 to the cells of the charged battery. The control port of each control converter is connected to its own analogue control circuit ACC1, ACC2, ACC3, ACC4. The control circuits

provide the charging process balancing of individual cells by correcting the common control signal MPT according to the actual values of the converter output voltage and current.

The MPPT controlling voltage corresponding to the model function (3) is generated in the implemented system by a non-linear analogue circuit in the analogue approximation generator (AAG).

The voltage U_a approximating U_{MP} is determined according to the working temperature t and the irradiation level G of the photovoltaic generator, according to the model function (Wolf, 2013).

$$U_a(t,G) = U_0(1 - \alpha t) + \beta \log(1 + G/\gamma)$$ (3)

where U_a (t, G) – an approximate voltage for temperature t and solar flux density G; U_0 – a reference voltage; α – a temperature coefficient of an approximate voltage and β, γ – constants.

The temperature-dependent voltage component U_a (t, G) is generated according to the voltage drop on the chain of silicon diodes which are placed in a heat contact with photovoltaic generator panels. The voltage drop across the diode chain shows principally the same temperature dependence as the U_{OC} voltage of the photovoltaic generator panels. After processing the voltage by a DC voltage amplifier with an adjustable reference level and gain, the output voltage of this amplifier in a wide range of temperatures is a very accurate image of the voltage U_{OC} of the PVG panels at a low level of irradiation.

The voltage dependence U_{OC} on the level of irradiation is compensated by the introduction of another correction component of the control voltage. This voltage is generated according to the current supplied by a small pilot PPV panel with a rated voltage of several V and current of several mA, located along with the PVG panels.

The correction component of the control voltage arises as a voltage drop on the non-linear resistive load, whose I-V characteristic approximates the logarithmic function of the voltage component U_a (t, G), which is dependent on irradiation. Since the total load impedance of the pilot panel is selected as low, the current supplied to the non-linear load is proportional to the panel irradiation, and the voltage drop corresponds to the PVG panel voltage U_{OC} dependence on the level of the irradiation.

The common MPT control signal for all controllable converters is generated by the charger control circuit according to the actual deviation U_{MP} from U_C voltage value at the RC input.

The approximate voltage U_a (t, G) is further compared by an analogue summator to the input voltage of the controllable U_c converters and according to their instantaneous values, a common U_{MPT} control signal is generated (4), where: A – amplifier gain.

$$U_{MPT} = -A \frac{R_c U_a(t, G) + R_a U_c}{R_a + R_c}$$ (4)

The control loop signal (CLS) of each converter, reducing its power transmission, is generated as a weighted sum of the MPT signal and the signals representing the deviations of the actual values of the cell charge voltage and current from the selected levels (5).

$$U_{CLS} = U_{MPT} + \delta(U_C - U_N) + \sigma(I_C - I_N)$$ (5)

where U_{CLS} – the control voltage of the cell converter; U_{MPT} – the voltage of the control signal MPT; U_C, I_C – the actual cell charge voltage and the current of the converter; U_N, I_N – the rated values of the cell charge and current; δ, σ – the constants.

RESULTS AND DISCUSSION

The technical solution aims to realize a simple, cheap and reliable device for charging batteries from a photovoltaic source. The power transmission from the PVG to the individual cell terminals is provided by a set of controllable low-power converters, whose number corresponds to the number of battery cells. However, the cost of the system does not differ so much from the cost of the converter with the rated power corresponding to the rated power of the system, since the cost of the commercially produced converters is approximately proportional to the rated power.

Compared to a conventional digital control system, it enables achieving both higher reliability and time response to the change of input values, and the construction simplification.

The photovoltaic system for charging LiFePO$_4$ batteries was implemented and tested during the summer 2018. The block diagram of the charging system is shown in Fig. 4. A photovoltaic generator was constructed as two in-parallel connected SUNRISE SR-M536100 panels (SR Module, 2019), having a firm position with a south orientation and a 45° slope. The battery was composed of four cells Winston-Battery WB-LYP100AHA (Winston-Battery, 2019).
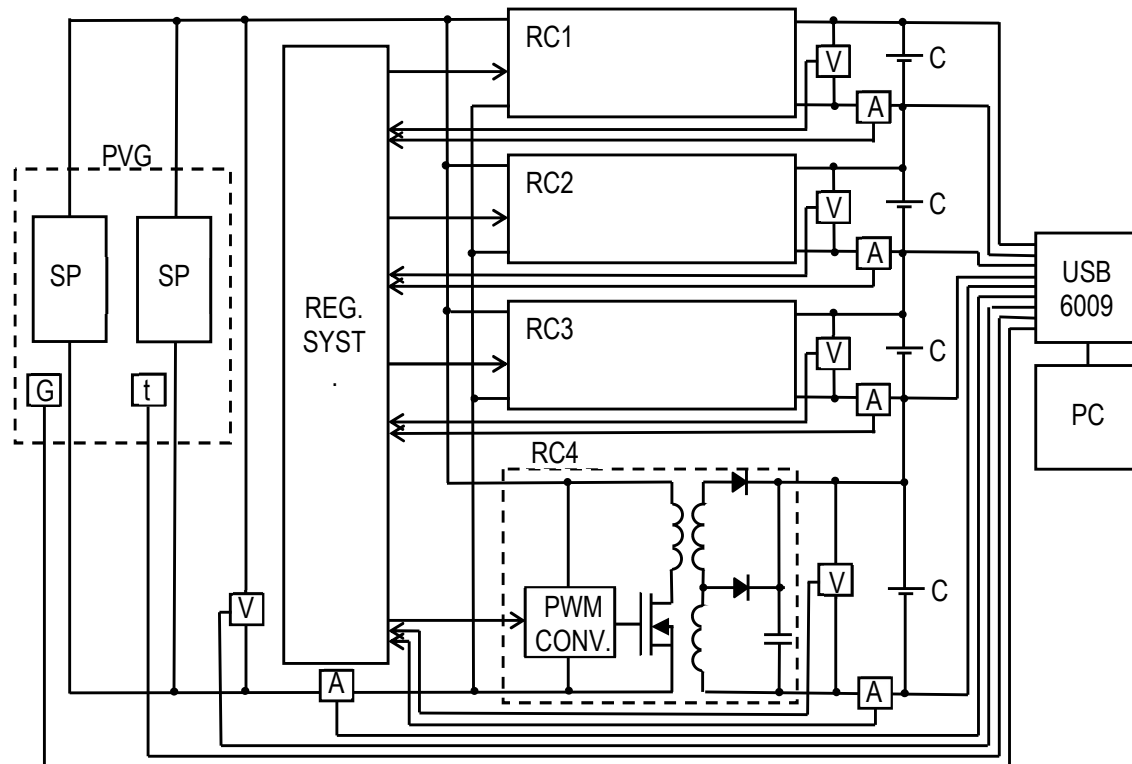

Figure 4. The block diagram of the charging system.

1187

Control converters were realized by adapted simple single-switch PWM DC/DC converters with a maximum output of 50 W, an input voltage of 15–30 V and an output voltage of 4 V. Actual power transmitted by the converters was controlled by the described control system. The operating state of the system was monitored by a computer system. The NI 6009 USB measuring card was used to enter the monitored voltages. Terminal voltages of battery cells, output voltage, current, temperature and PVG irradiation were scanned. Labview SW was used for data procession on a PC.

A typical course of the basic operating values of the charger in charging during the day time is shown in Fig. 5. Although the solar flux density reached a maximum of 970 Wm^{-2}, its course during the day was decisively influenced by the cloudiness. During the day it was calm, so the maximum temperature of the panels reached up to 50 °C. The power, greater than 25% of the rated power, was supplied by PVG only from 9:00 to 13:45.
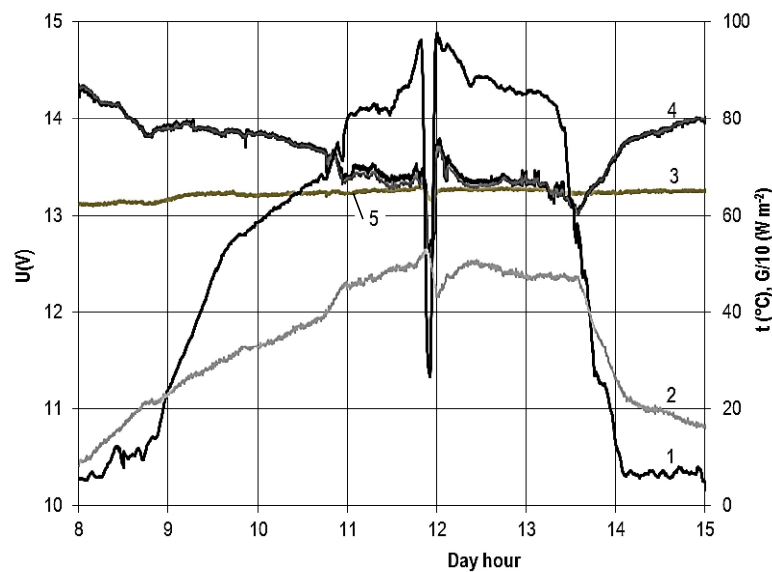

Figure 5. Course of PVG irradiation (curve 1), panel temperatures (2), battery terminal voltage (3), approximate voltage (4) and PVG output voltage (5) during the day time.

The function of the control system is illustrated by the courses of the approximate voltage $U_a(t,G)$ and output voltage of a photovoltaic generator U_c. The control loops of the converters ensure a good match of the voltage U_c with the approximate voltage $U_a(t,G)$. A maximum deviation at the highest transmitted power reaches approximately 1%.

The charging process of the battery is illustrated by the increase in its terminal voltage U_{bat} during charging, but regarding the variable value of the charging current, the indicated course is distorted due to the internal resistance of the battery.

Fig. 6 illustrates the comparison of the courses of the actual output power of the photovoltaic generator with the generator power calculated according to the solar flux density during the day time. The calculation was performed using the approximation by a direct proportion with regard to the PVG rated power of 200 W at the solar flux density of 1,000 Wm^{-2}.

1188

The maximum actual power deviation from the calculated value is 6–8%. The decrease in actual power is caused by the increase in PVG operating temperature at high solar flux density levels, which was not considered in the calculation.
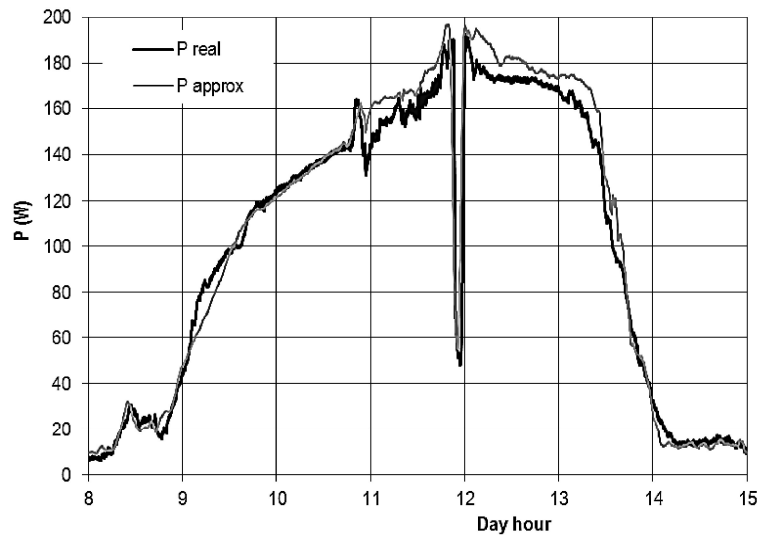

Figure 6. Comparison of the approximated and measured PVG output power courses during the day time.

The real dependence of the charging system power on the intensity of the solar flux density is shown in Fig. 7. The dependence corresponds to the direct proportion when considering the 96–97 W rated power of the panels
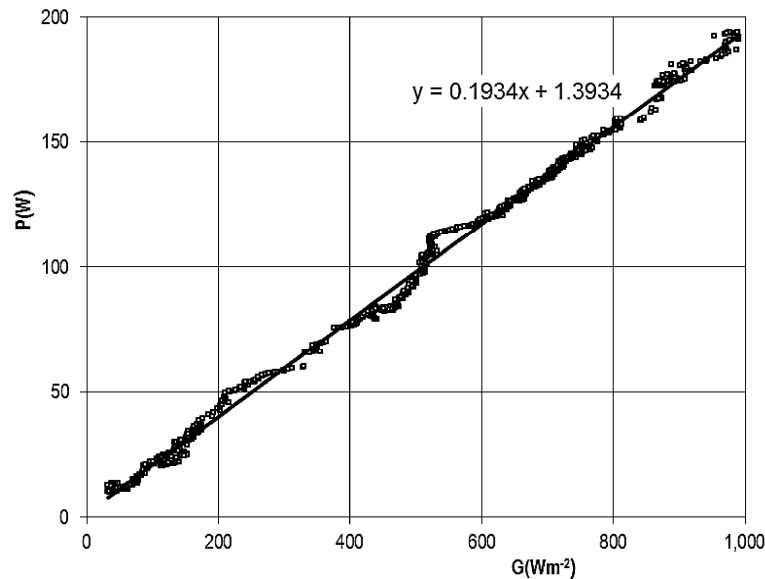

$$y = 0.1934x + 1.3934$$

Figure 7. Dependence of the measured power of the charging system on the solar flux density and its approximation characteristic.

CONCLUSIONS

The control system automatically ensures the operation of the photovoltaic generator in the close proximity to the MPP. The charging processes of the individual battery cells are simultaneously balanced, i.e., the individual cells are protected against overcharging. The control system works exclusively in an analogue mode and does not comprise a computer, which significantly reduces its acquisition costs. By an individual control of the charging processes of the battery cells, there is no need to use cell balancers. This further simplifies the construction of the system, reduces its power losses and increases its reliability compared to the commercial computer-controlled systems.

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