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Innovative system for energy collection and management integrated within a photovoltaic module

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Abstract

The dynamic development of battery technology and design based on the flow of lithium ions, which is mainly driven by the needs of the automotive industry, leads to the conclusion that these batteries are becoming a more viable alternative to traditional lead-acid batteries. Their use is driven by their ability to charge and discharge quickly, higher durability, maintenance-free operation, much smaller dimensions, and lighter weight. The emergence of super-thin LiFePO₄ battery technology inspired the design and implementation of a prototype of a portable photovoltaic module that is integrated with the battery and an innovative system for data gathering and power management. This paper presents a block diagram of a prototype and discusses issues related to the selection of components and the design and implementation of individual blocks. In particular, it considers an innovative system that quickly and accurately supports the elevation and declination angle of the module and the system for monitoring the state of battery charge and discharge.

31 Basic technical parameters are described, as well as the possibility of scaling up the system.
32 Mechanical construction details, the concept of research stations, and the results obtained
33 during the research are presented. An analysis of the areas of application and economic
34 aspects of the solution are also taken into consideration.

35 **Keywords:** stand-alone photovoltaic system, data gathering and power management,
36 integrated battery, super-thin LiFePO₄ battery, charge/discharge controller, battery status
37 monitor

38 **Introduction**

39 The worldwide growth of photovoltaics (PV) has followed an exponential curve for more than
40 two decades. During this period, PV has evolved from a pure niche market of small-scale
41 applications towards becoming a mainstream electricity source. Regardless of the global trend
42 of attaching large installations to the grid, off-grid electrification is still the main approach to
43 accessing electricity in countries and areas with little access to electricity.

44 The term “off-the-grid” can refer to living in a self-sufficient manner without relying on one
45 or more public utilities. Decentralized electricity production, defined as electricity-based
46 production within a village that is not linked to a grid or to transmission or distribution
47 networks, provides a plausible medium-term solution to the electricity accessibility issue in
48 some countries that are suited to solar energy (for example, India and Nigeria). According to
49 the IEA (2009), 1.456 billion people worldwide (18% of the world's population) do not have
50 access to electricity, and 83% of these people live in rural areas.

51 The availability of energy is an important pre-condition for developing the national economy
52 and improving the living standards of people. The application of PV-based home
53 electrification will offer a quick, economic, and reliable answer to the need for power in rural
54 households, especially those using light-duty appliances.



55 Therefore, there needs to be an assessment of the potential of a solar PV-based rural home
56 electrification project that will meet the basic energy needs of rural homes without increasing
57 stress on the power grid.

58 The domestic load demand of rural areas, which will serve as input data in the design of PV-
59 based rural home electrification systems and also assist governments in their rural
60 electrification planning framework, has been assessed. For example, rural households in
61 Nigeria will require 850.8 kWh/yr to meet their basic power requirements for loads such as
62 lighting and electronic appliances (for example, radios and televisions) [1]. The governments
63 of these countries recommend that solar PV-based rural home electrification applications
64 should be encouraged.

65 In most rural regions, villages are located 3 to 80 km (or even further) away from the existing
66 grid in difficult areas like forests, hills, and deserts. The number of households in a village
67 may range between 2 and 200 with a dispersed distribution of loads. The power demand of
68 villages is quite low, and rural domestic consumers are mainly peak-time consumers who
69 contribute low load factors of 0.2–0.3 [2].

70 Stand-alone PV systems can be implemented with single components or assembled and
71 integrated by the manufacturer. A kit of this kind is often called a ‘solar home station’. A
72 solar home station is a portable kit designed specially to meet basic domestic power
73 requirements in grid-isolated, high-temperature regions of the world. Elements of such
74 autonomous systems are a PV module or modules, an electronic controller, and battery
75 charging. The nominal voltage of the system battery in such a kit is usually 12, 24, or, less
76 frequently, 48 V. In cases where the installation provides power to consumers, which requires
77 alternating voltages of 110 or 230 V, an appropriate electronic DC/AC converter is required.
78 Typical home appliances that can be powered by the system are colour TV, radio, lighting,



79 computers, mobile phones, and ventilation (fans). It can also be the source of electric power
80 for military applications, security signalling and lighting, and charging mobile phones. There
81 are many examples of such systems offered by manufacturers.

82 Figure 1 shows an example of such a system designed and built by the German company
83 Solar Fabrik AG (left) [3], as well as one built by the Institute of Electron Technology
84 Division in Krakow, commissioned by Sunflower Farm (right).

85 As the solar market grows worldwide, the importance of implementing deep-cycle batteries as
86 the energy storage component for renewable energy systems is critical. These systems are
87 typically based on so-called "long life" lead-acid solar batteries; they are therefore bulky and
88 have a limited lifespan of typically five years. The first problem that must be faced is
89 reducing the size and weight of the system. The second one is extending the lifetime of the
90 energy accumulator in order to bring it closer to the lifetime of the PV module. In addition to
91 their degradation capacity, lead-acid batteries are characterized by large dimensions and a low
92 resistance to freezing temperatures. These shortcomings have led to increased interest in
93 lithium-ion technology in PV installations. Simultaneously, a significant reduction in prices
94 is projected due to the effect of increasing the scale of production, which is likely to translate
95 into achieving a market advantage over storage solutions based on lead-acid technologies.

96 Unlike lead-acid technology, lithium-ion batteries have a much longer life span. After about
97 500 charge/discharge cycles, cyclic-operation standard gel batteries show a significant
98 reduction in capacity; under the same conditions, lithium-iron-phosphate (LiFePO_4) batteries
99 withstand about 3,000 charge/discharge cycles. The lifetime of such a lithium-ion battery is
100 much closer to the lifetime of a PV module and electronic controller, which will allow a
101 commercial device with high cumulative stability to be offered in the future. The big
102 advantage here is the possibility of LiFePO_4 batteries charging and discharging large currents



103 of the order of 1 C, while lead-acid batteries can operate at currents of up to 0.3 C. The main
104 disadvantage of lithium-ion technology is its sensitivity to the conditions of charging and
105 discharging processes, which can lead to significant degradation of battery capacity and,
106 eventually, destruction of the battery. Unlike lead-acid batteries, rechargeable batteries based
107 on LiFePO₄ technologies require the use of the electronic management system.

108 The primary objective of the scheme is to equalize the charge level of cells in the package (in
109 the process of both charge and discharge cycles), to measure temperature and prevent the
110 battery from exceeding its temperature limit, and often also to monitor and inspect the
111 discharge process. These systems may be based on dedicated integrated circuits, which are
112 offered by most leading manufacturers.

113 The third problem to be solved is the partial shading of the PV module. The reduction in
114 power output caused by the accumulation of dust on the PV module surface is an important
115 problem. Dust is created from powdered grains of sand and particles of different bodies. Dust
116 originates from different sources, for example from soil and volcanic eruptions. Dust in the air
117 is an aerosol and, in high concentrations, can cause climate change. The deposition of
118 airborne dust on PV modules may decrease the transmittance of solar cell glazing and cause a
119 significant degradation in the solar conversion efficiency of PV modules. Many researchers
120 have devoted their work to studying the origin, composition, and gradation of dust grains
121 originating from different regions of the world [4]–[7] and their influence on PV module
122 performance.

123 **Materials and Methods**

124 A PV module integrated with an accumulator and an innovative system for data gathering and
125 power management was built on the basis of the block diagram illustrated in Figure 2.

126 Figure 3 presents details of the construction of the PV module integrated with the accumulator
127 and innovative system for gathering and power management.

128 PHOTOVOLTAIC MODULE

129 The basic element of the structure is the monocrystalline PV module, RS 36-125*125M-100,
130 which has dimensions of 1193 mm × 539 mm × 25 mm, weighs 7.6 kg, and is manufactured
131 by Risen Energy Co. It has a nominal power of 100 W, open voltage of $V_{oc} = 22.8$ V, and
132 short circuit current of $I_{sc} = 6.03$ A. The voltage at the point of maximum power is $V_{MPP} =$
133 18.4 V and the current at the point of maximum power is $I_{MPP} = 5.43$ A.. The solution allows
134 for a structure with dimensions that do not exceed the dimensions of the PV module.

135 BATTERY

136 LiFePO_4 batteries are fairly new for solar use. They have no toxic chemicals and offer four
137 times the power density at a third of the volume compared to lead-acid batteries. Laboratory
138 results indicate that 2000 to 5000 cycles can be expected from a well-maintained LiFePO_4
139 battery bank; a battery will still deliver more than 75% of its capacity after 2000 cycles. In
140 contrast, even the best deep cycle lead-acid batteries are typically only good for 500–1000
141 cycles. LiFePO_4 batteries have almost no self-discharge – they can stay disconnected without
142 any problems for 10 months and will still be almost fully charged.

143 LiFePO_4 batteries appear well-suited for off-grid renewable applications. They show not only
144 the least degradation under variable charging protocols, which are characteristic of all types of
145 off-grid renewable energy generation, but also the best voltage performance. Their long
146 lifetime would reduce the frequency of battery replacement of solar systems [8].



147 We propose that the Nanophosphate® Lithium Ion Prismatic Pouch Cell be combined with
 148 the 100 W monocrystalline PV module. Nanophosphate® is a positive electrode material with
 149 a remarkable rate capability, which is critical for high power systems. The cell dimensions of
 150 a single 19.6 Ah (minimum) cell capacity are equal to 7.25 mm × 160 mm × 227 mm. Four
 151 cells connected in series to form a battery with a rated voltage of 13.2 V and a capacity of 20
 152 Ah were used. However, the dimensions of the back cavity of the module even allow the use
 153 of a complex battery of 12 cells connected in series and in parallel with a total capacity of 60
 154 Ah. The advantages of Nanophosphate® are its higher charge and discharge rates, which lead
 155 to better performance and efficiency, a wide SOC (State of Charge) range, enabling greater
 156 battery utilization, superior abuse tolerance, and long battery life for both deep and shallow
 157 cycling [9]. Table 1 presents the specifications of the A123 AMP20 battery.

158 Table 1. AMP20 cell specification [9]

Dimensions [mm]	7.25 × 160 × 227
Mass [g]	496
Capacity (minimum) [Ah]	19.6
Voltage (nominal) [V]	3.3
Energy content (nominal) [Wh]	65
Discharge power (nominal) [W]	1200
Maximum discharge current [A]	100
10 s discharge current [A]	600
Cycles (depth of discharge = 90%)	3000
Operating temperature [°C]	-30 to 55
Storage temperature [°C]	-40 to 60

159 The system is also equipped with a commercial accumulation-type module, PCM-L04S25-
 160 808 12.8/20A for LiFePO₄ (4S), to balance the individual cell voltages. This system also
 161 protects the cells against overload, excessive discharge, short circuiting, and overheating. The
 162 main parameters are summarized in Table 2.

163 Table 2. Technical parameters of the PCM-L04S25-808 module [10]

Maximal continuous charging current [A]	20
Maximal continuous discharging current [A]	20
Balance current for single cell [mA]	72 ± 10
Balance voltage for single cell [V]	3.6 ± 0.025
Overcharge detection voltage [V]	3.9 ± 0.025
Overcharge release voltage [V] [V]	3.8 ± 0.025
Over-discharge detection voltage [V]	2.0 ± 0.05
Over-discharge release voltage [V]	2.3 ± 0.05
Dimensions [mm]	$70 \times 60 \times 9$

164 BATTERY CHARGE CONTROLLER

165 The model controller was designed and manufactured based on an LT 8490 dedicated
 166 integrated circuit [11]. It was examined by the manufacturer by providing samples and
 167 informative materials before placing it on the market. Its schematic diagram is shown in
 168 Figure 4; a photograph of it is shown in Figure 5.

169 Use of the LT 8490 system made it possible to:

- 170 • obtain a broad range of input (6–80 V) and output (1.3–80 V) voltages due to an
 171 implemented DC/DC buck-boost,

- 172 • obtain a very high efficiency,
- 173 • search for the real point of maximum power even when the module was partially
- 174 overridden,
- 175 • adapt to the needs of both lead-acid batteries and LiFePO_4 by employing a CC/CV
- 176 (constant current/constant voltage) charging algorithm,
- 177 • enable cooperation with other energy sources,
- 178 • carry out compensation of the effect of changes in the ambient temperature.

179 BATTERY DISCHARGE CONTROLLER

180 A battery discharge controller was developed and manufactured for discharge process
181 management (Figure 6). It protects the battery from deep discharge and from a discharge
182 current that is too high. The protection against a discharge current that is too high takes into
183 account the possibility of temporarily exceeding the maximum permissible discharge current
184 and exceeding the average value of the current in a given period of time.

185 Of particular note is the use of a commercial, fully integrated Hall-effect-based linear current
186 sensor of type ACS 712 ELCTR-30 A-T, optimized for the measurement of currents up to 30
187 A with input resistance of $1.2 \text{ m}\Omega$ and MOSFETs for very a low value of $R_{\text{DS(on)}}$ of $1 \text{ m}\Omega$,
188 allowing for a substantial reduction of power and preventing waste in the system.

189 The use of a highly energy-efficient DC/ DC converter of type LT 3970, lowering the voltage
190 to 5 V, and the ability to switch off the current sensor and OLED display allow additional
191 saved energy to be stored in the battery. This is particularly important especially in the final
192 phase of discharge of the battery. The OLED display used had low power consumption and
193 high contrast. Figure 7 shows the manner of displaying the selected parameters.

194 The use of an ATmega88 microcontroller and the dedicated software allows for the
195 measurement of battery voltage and charge and discharge currents and provides the



196 opportunity to read them on the OLED display. The observation of changes in the battery
197 charging current makes it possible to choose the optimum elevation angle and declination
198 demonstrator settings. It is possible to set the value of all parameters via RS-232.

199 It is possible to expand the system with a battery SOC monitor, enabling determination of the
200 amount of energy currently stored in the accumulator, and the function of remote reading of
201 data through the use of a dedicated application for mobile smart phones.

202 **Results**

203 A research station was designed and constructed for the purpose of the experiment. The block
204 diagram is shown in Figure 8.

205 The following equipment was used for measuring voltages and currents:

- 206 – Keithley 2700 digital multimeters with a resolution of 6 1/2 digits, equipped with a
207 Keithley 7700 twenty-channel universal multiplexer card,
- 208 – two Keithley 1651 shunts (R1, R2) for an ammeter, 50 A, 0.001 Ohm, $\pm 1\%$,
- 209 – AgilentE4350B/J03 simulator of PV modules, 10 A, 480 W, with the author's
210 management software and the commercial software Solar Design Studio v6.0,
- 211 – BK 8510 programmable electronic load, allowing for the measurement of
212 characteristics of the discharge mode CC, CV, constant power (CP), and constant
213 resistance (CR),
- 214 – personal computer (PC),
- 215 – type LI-250 pyranometer equipped with an LI200 probe,



216 To measure the temperature of individual elements of a system, a Thermo-Hunter model BS-
217 02T non-contact thermometer with a measuring range of 0–500 °C and accuracy of $\pm 1\%$ was
218 used.

219 Measurements were carried out with the use of an Endeas QuickSUN 820A commercial solar
220 simulator with a manual measuring system. Electrical parameters of the module were
221 determined for the STC (Standard Test Conditions: irradiation = 1000 W/m²; temperature =
222 25 °C; radiation spectrum: AM1.5). This type of simulator is a high-performance device
223 equipped with a Xenon flash. It allows for the determination of the full current-voltage
224 characteristics of the module while maintaining the AAA class. This class is determined in
225 accordance with IEC 60904-09, edition 2. The simulator has the appropriate filters for the
226 preservation of the spectrum AM1.5 uniformity and an adequate distribution of radiation over
227 the entire surface of the test module. In addition, the test stand has additional generators that
228 allow for an extension of the duration of the flash so that the parameter LTI (Long Term
229 Instability) complies with the conditions of class A.

230 The management program is written in Delphi and is designed to work on PCs with Windows
231 XP and later. It enables, via the RS232 interface or USB, the remote management and
232 monitoring of the simulator, electronic load, and multimeter with the scanner. Thanks to this
233 program, any experiment involving charging and discharging the battery and recording
234 voltage as a function of time at the five points of the system can be realized. The system
235 makes it possible to carry out research in real and simulated conditions.

236 Exemplary results of the characteristics of the RS 36-125*125M-100 module generated by the
237 simulator are shown in Figure 9.



238 For the examination of the MPP (Maximum Power Point) search accuracy, the simulator was
239 used to generate: 1) the output characteristics of a typical 12 V monocrystalline silicon
240 module for solar irradiation of 100, 200, 400, 600, 800, and 1000 W/m² (Figure 10), and 2)
241 the characteristics of the partially overridden module (Figure 11).

242 The point where the red lines cross shows the precision of the MPP search. The search time is
243 completed within seconds. An analysis of the behaviour of the regulator through the testing of
244 input-output characteristics of the module leads to the conclusion that the system is working
245 properly and in accordance with our expectations. The MPP search is completed in a fast,
246 precise, and correct manner in the case of the partially shaded modules. The behaviour of the
247 system in the case of low solar irradiation of the module surface (100 W/m²) is also highly
248 promising.

249 Experimental studies concerning the impact of partial shading of the PV module on the
250 electrical power generated were carried out with the use of the modules produced on the basis
251 of monocrystalline silicon cells of type SF 110 with the following basic parameters: $P_{MPP} =$
252 110 W, $V_{OC} = 21.6$ V, $V_{MPP} = 17.4$ V, $I_{MPP} = 6.32$ A, and $I_{SC} = 6.76$ A. Modules SF 150/10A-
253 155 have the following basic parameters: $P_{MPP} = 110$ W, $V_{OC} = 21.6$ V, $V_{MPP} = 17.4$ V, $I_{MPP} =$
254 6.32 A, and $I_{SC} = 6.76$ A. Modules 85S-12B have the following key parameters: $P_{MPP} = 85$ W,
255 $V_{OC} = 22.5$ V, $V_{MPP} = 17.8$ V, $I_{MPP} = 4.80$ A, and $I_{SC} = 5,15$ A.

256 A study of the partially shaded module, with an override of $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, and 8 cells, was also
257 conducted. Based on the analysis of the graph in Figure 12 it can be concluded that in the case
258 of the $\frac{1}{4}$ and $\frac{1}{2}$ shaded cells, the MPP point, is located in the vicinity of about 0.8–0.9 V_{oc} ,
259 while the rest of the points are shifted and occur in the vicinity of 0.5 V_{oc} [12–15]. Based on
260 numerous studies of commercial charging controllers, it was found that most of them cannot
261 find the MPP in the case of an unusual location. To solve this problem, a dedicated controller



262 chip that was able to find the abnormal locations by searching for locally positioned MPP
263 points was used.

264 It was possible to measure the characteristics and precise charging time of the battery.

265 Examples of battery charging characteristics from a PV module simulator for 1000 W/m^2 and
266 a temperature of $25 \text{ }^\circ\text{C}$ are shown in Figure 13. Solar energy was used to charge the batteries.
267 During charging, the irradiation varied between 800 and 1000 W/m^2 ; the charging time was
268 approximately 3 hours. The charging process was monitored with the use of a charge
269 controller, and this was continued until the terminal voltage of the battery reached the value of
270 $14.2 \pm 0.15 \text{ V}$. The examination of the loading process was initiated with the simulation of
271 typical output characteristics of the PV module of $12 \text{ V}/150 \text{ W}$.

272 After charging the battery, the subsequent process of battery discharge was carried out with
273 sequence currents of 5, 10, and 20 A (Figure 14). Discharge times were, successively, 3 hours
274 50 minutes, 1 hour 54 minutes, and 55 minutes.

275 **Conclusions**

276 The proposed solution is an interesting and much more mobile alternative to a solar home
277 station, which was described in the introduction. It is also planned to further increase the
278 mobility of the implementation of the version shown in Figure 15.

279 The designed and examined innovative gathering and energy management system integrated
280 within a PV module meets the requirements for stand-alone power stations and tackles the
281 previously identified problems: it is an integrated system with minimized dimensions and
282 weight, allowing for operation with maximum power point control and power settings for an
283 optimal angle of elevation and declination.



284 Similar results were obtained with PV systems for charging the batteries of electrically
285 powered vehicles, where high system efficiency was achieved by directly charging the battery
286 from the PV system and matching the PV maximum power point voltage to the battery
287 charging voltage at the desired maximum state of charge of the battery [16].

288 The system can be used for camping, in gardens and allotments, on vessels, in mobile
289 monitoring, warning, and information systems, and so on. It has been registered with the
290 Polish Patent Office under patent no. P.410653 [17].

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Figure 1. Exemplary autonomous photovoltaic systems called ‘solar home stations’



Figure 2. Block diagram of the photovoltaic module integrated with the accumulator and innovative system for data gathering and power management

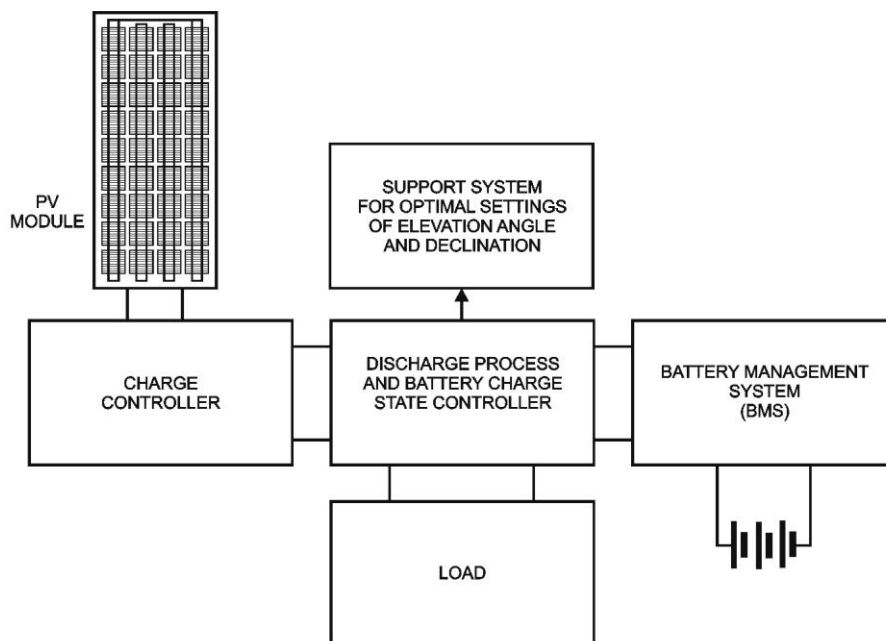


Figure 3. Details of the construction of the photovoltaic module integrated with the accumulator and innovative system for data gathering and power management

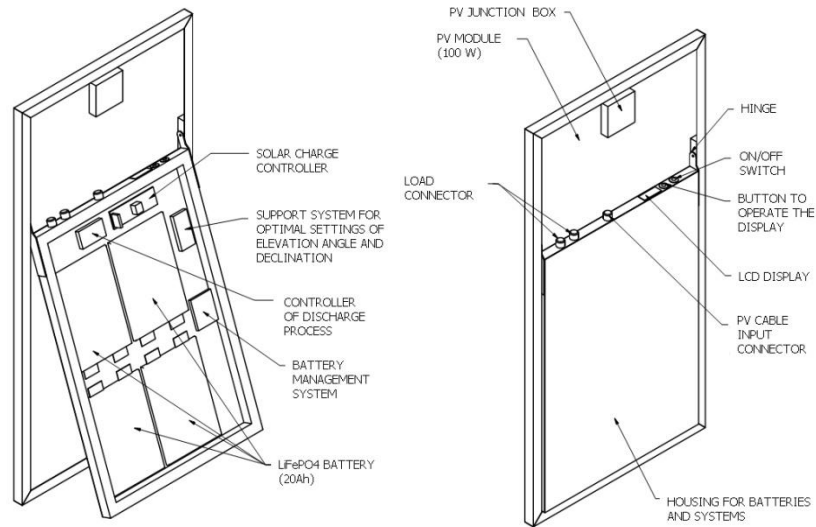


Figure 4. Schematic diagram of the battery charge controller

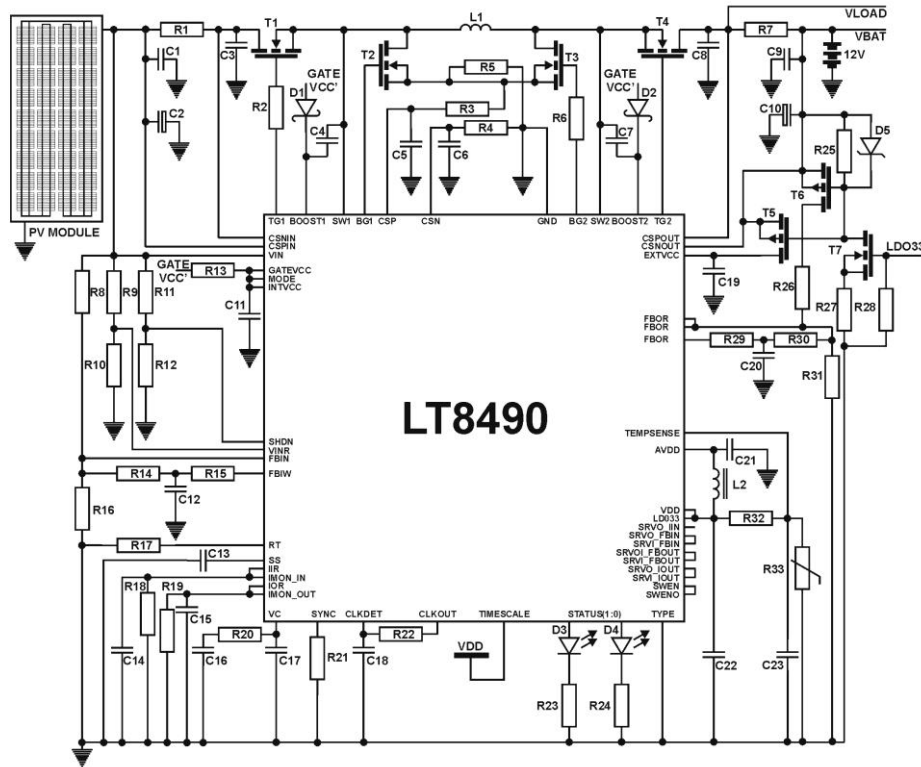


Figure 5. View of charge controller

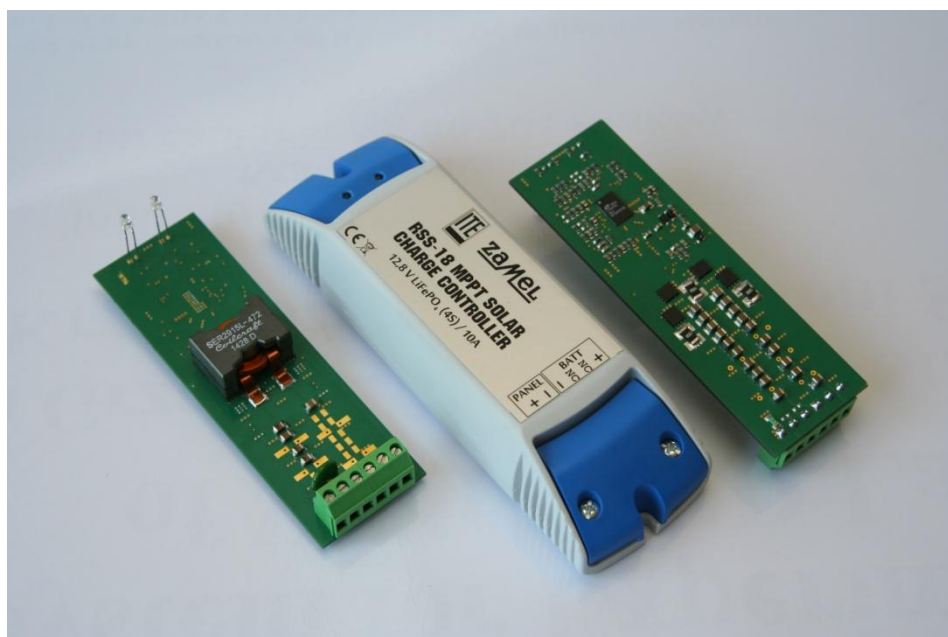


Figure 6. Schematic diagram of the battery discharge controller

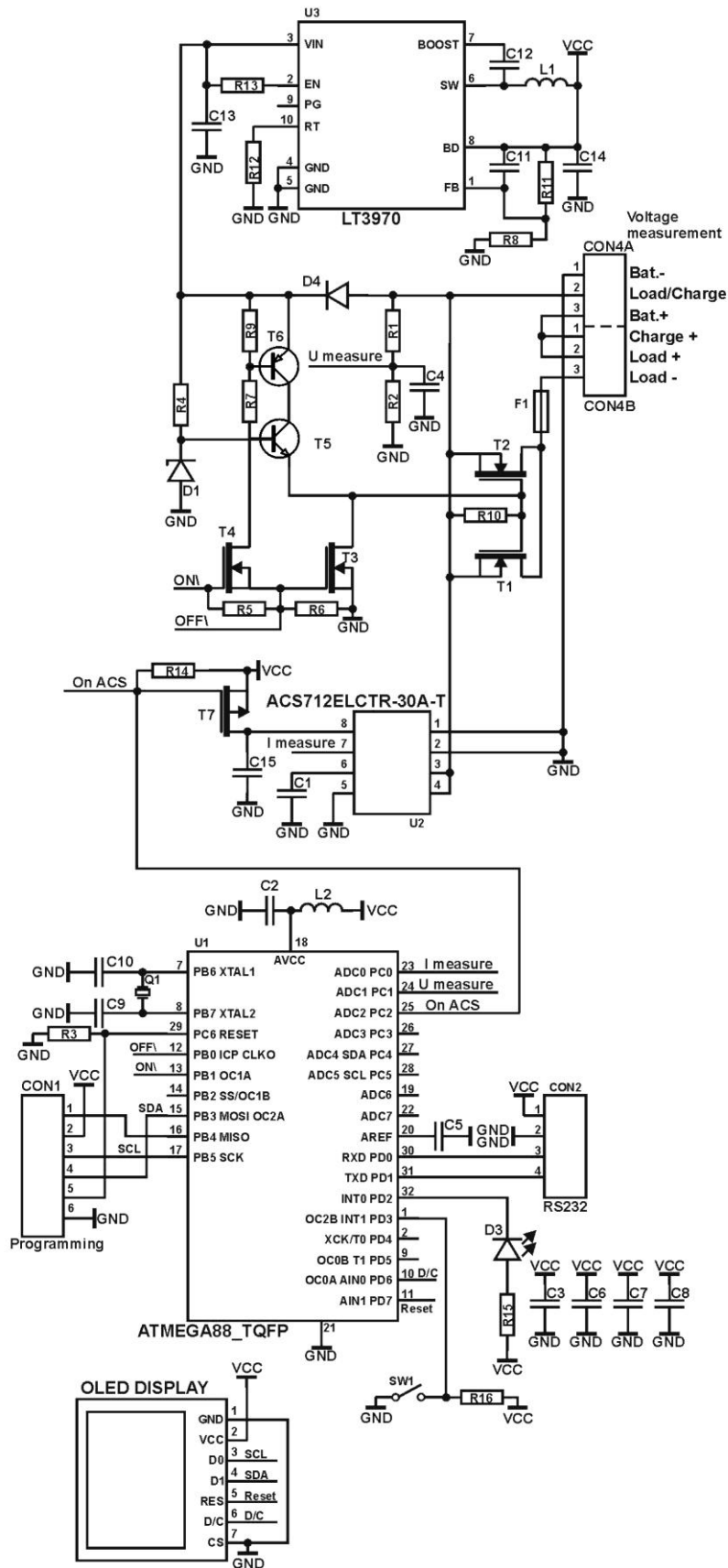


Figure 7. The manner in which the selected parameters are displayed



Figure 8. The scheme of the system for measuring the current-voltage characteristics of the module under different lighting conditions

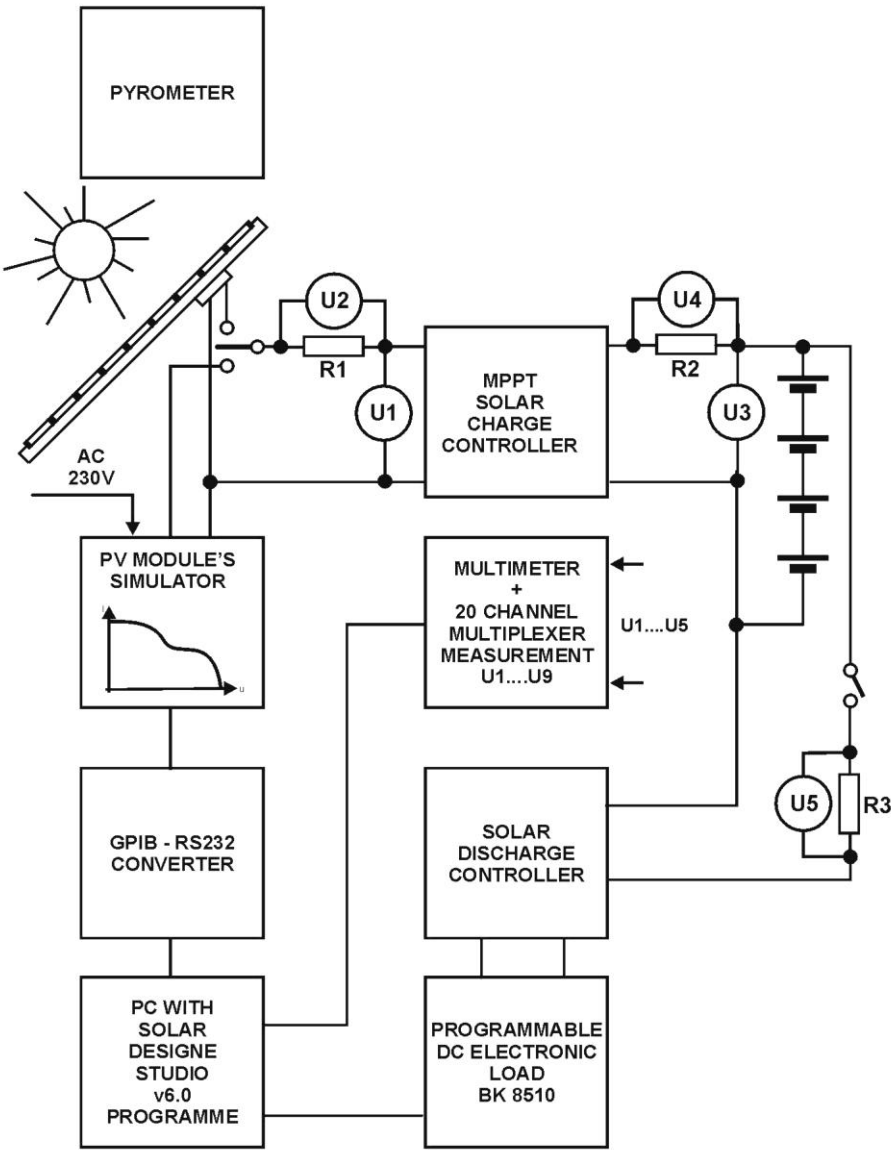


Figure 9. Exemplary characteristics of RS 36-125*125M-100 module

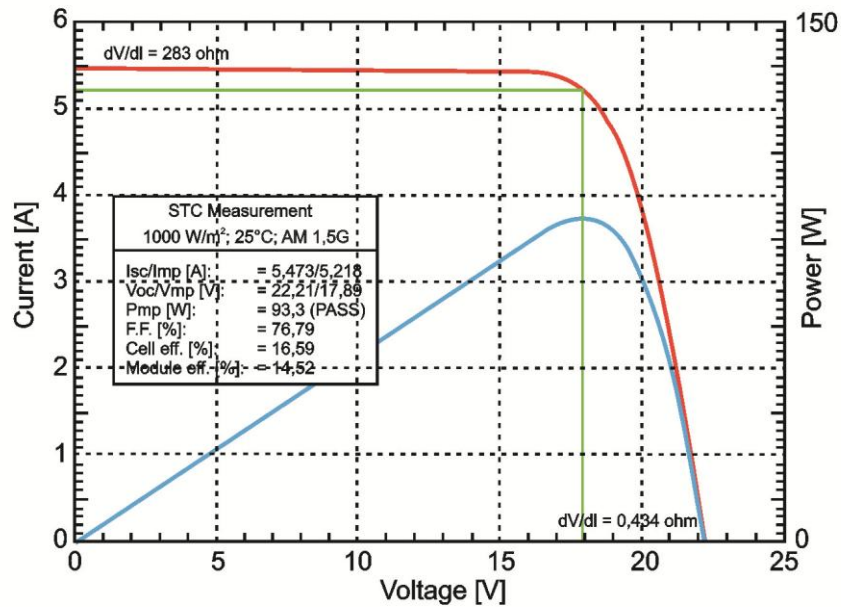


Figure 10. Current-voltage characteristics of the silicon monocrystalline module for irradiation of 200, 400, 600, 800, and 1000 W/m² and a temperature of 25 °C

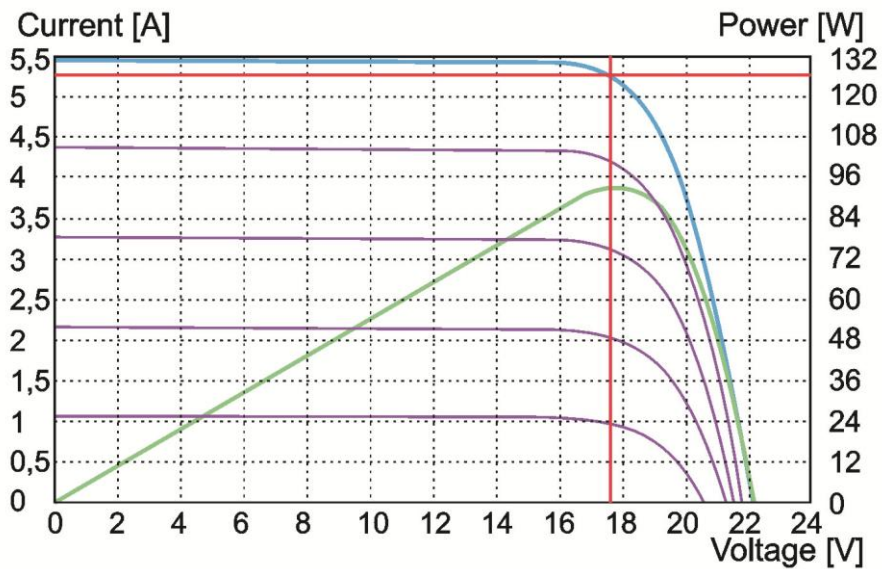


Figure 11. Characteristics of the partly shaded modules

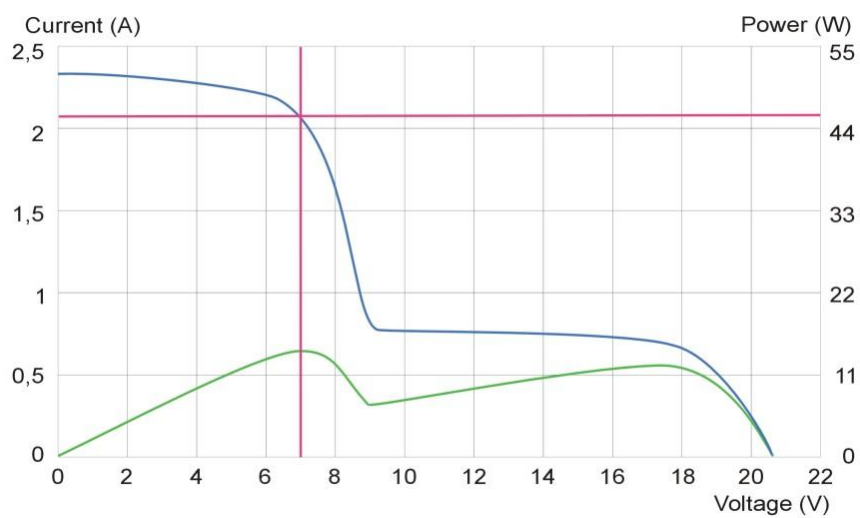


Figure 12. Dependency of the power generated by the SF 150/10A-155w module as a function of different shading configurations A–F

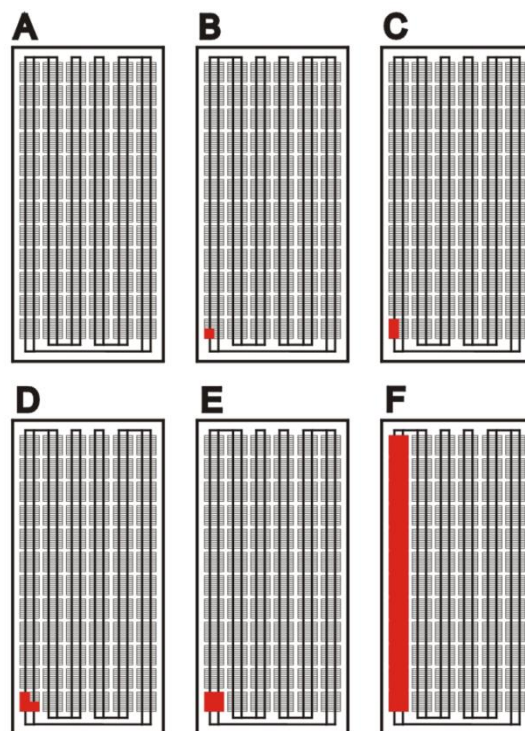
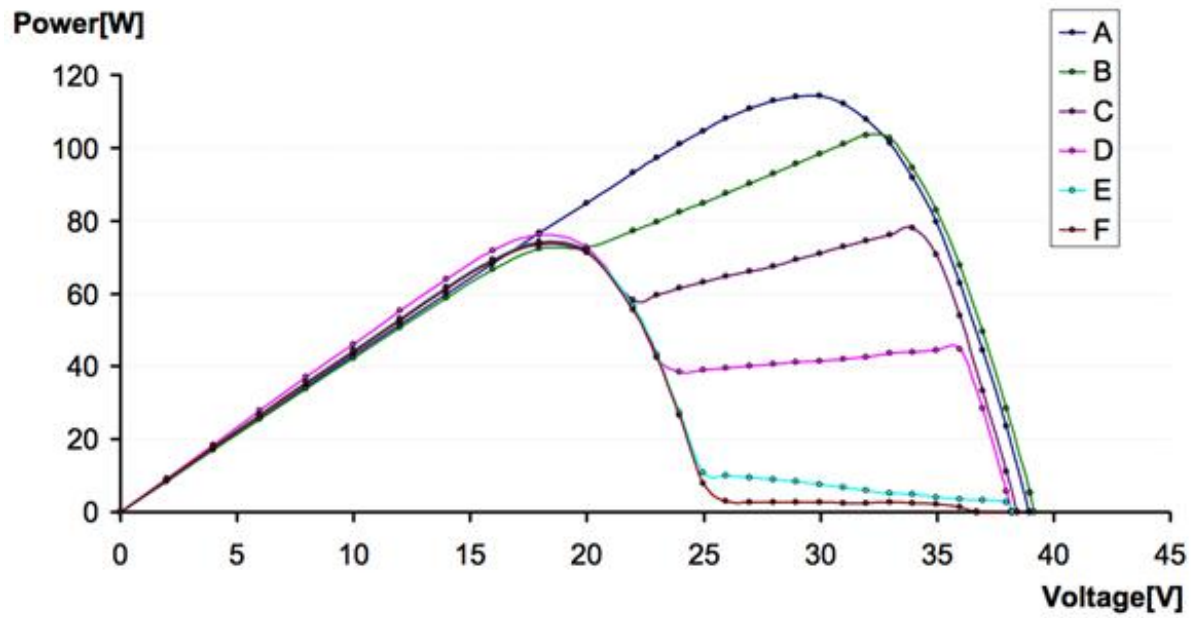


Figure 13. Characteristics of battery charging

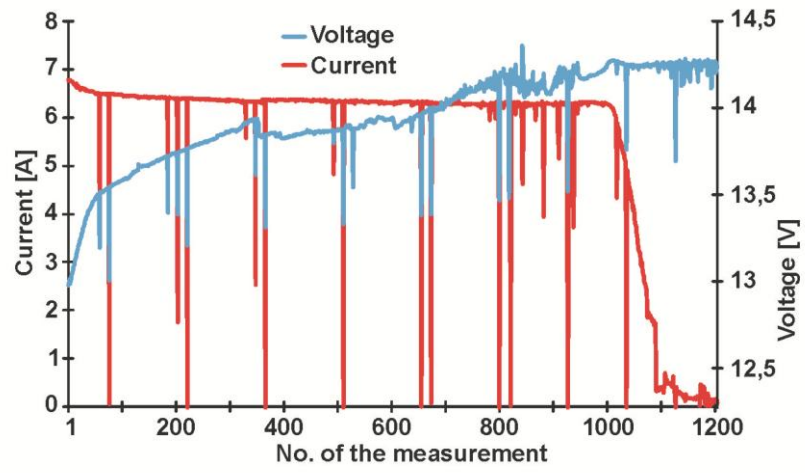


Figure 14. Discharge characteristics for the load currents of 5, 10, and 20 A

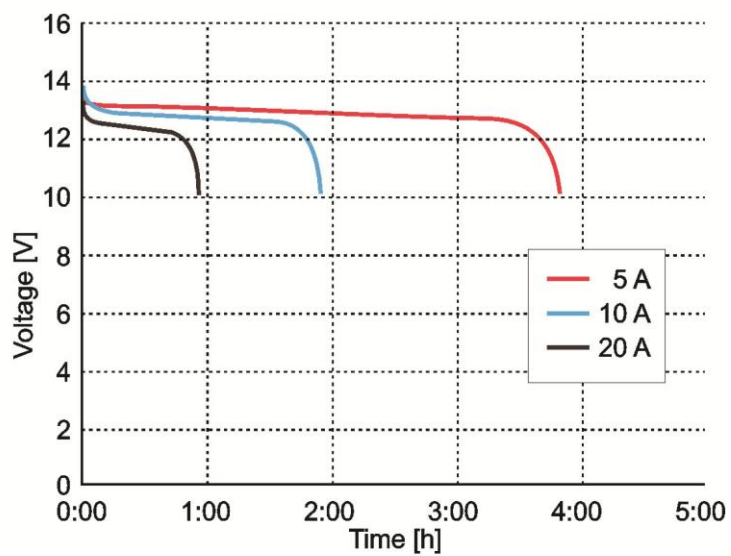


Figure 15. External view of the version with increased mobility

