Battery charging controllers in autonomous photovoltaic systems

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In the work, the authors explain the concept of operation of an autonomous photovoltaic system with particular focus on the role of battery charging controllers. Didactic experiments that complement the theoretical knowledge on the construction and the principles of operation of photovoltaic systems of the “off-grid” type were conducted. The laboratory set described provides the capabilities to analyze the operation of small autonomous photovoltaic systems which are analogous to complex systems that are used in real settings. The systems are especially popular in Poland and that is why it is important to deepen the knowledge on them. Particular attention is put in the article on the cooperation of photovoltaic elements with energy storage devices (condensers and batteries) and with the load points with the use of battery charging controllers (serial and shunt) and of a module protecting the energy storage devices against discharging. The review of different solutions is complemented with sample measurement tests and with the test results for the tested system of the “off-grid” type.

1. Introduction

The solar power industry is becoming more and more popular and it starts to be visible in a more and more wider scope of applications. Solar radiation is used by many countries of the world in power engineering and industry. Solar power plants with the capacity of a few kilowatts to a few hundred megawatts are already operational. The total production of PV cells (Fig. 1) and the capacity obtained from photoelectric conversion (Fig. 2) is constantly growing. All of this stimulates constructors, investors, and users to search for optimal solutions with respect to their efficiency and profitability. Since the time when the first photovoltaic cell was invented in the early fifties of the last century in the laboratories of the American Bell company, new solutions aiming at increasing the energy efficiency of photocells have constantly been explored. In recent years, a considerable increase in the number of installations based on photoelectric conversion has been noted in well developed countries. Similar trends also start to appear in Poland; the decreasing price of photovoltaic cells and associated installations promises their wider use in the upcoming years.

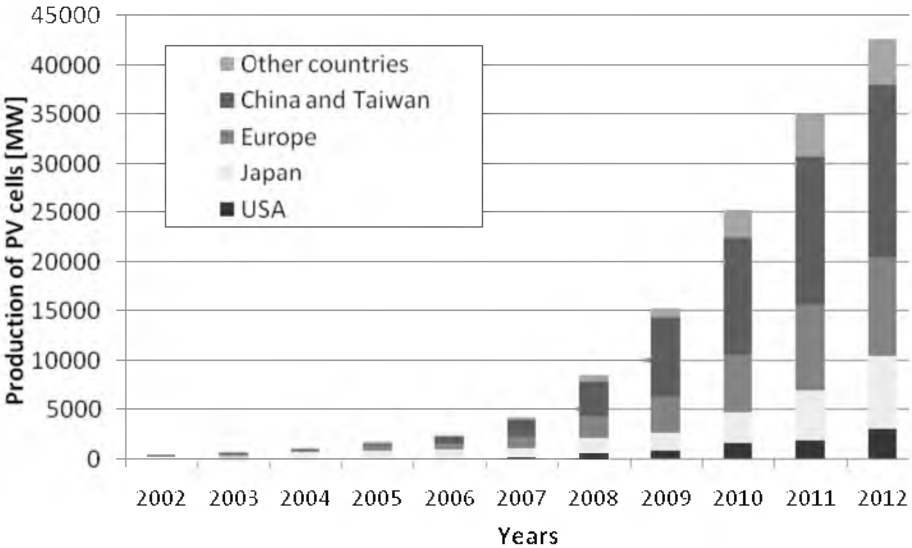
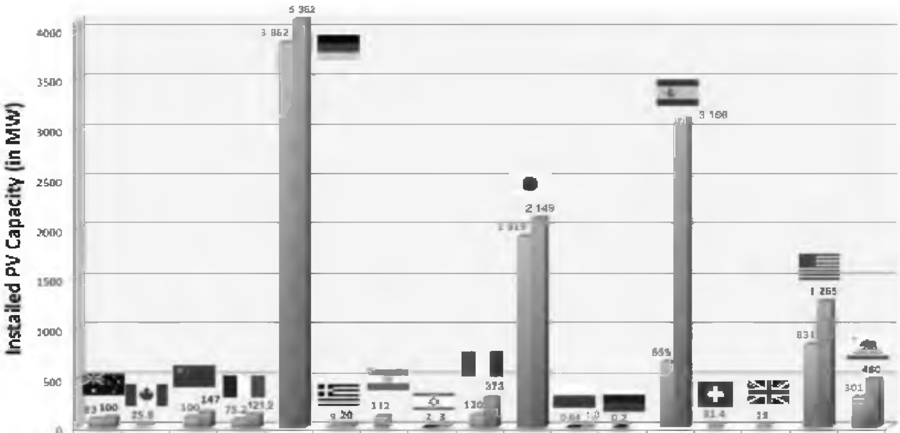


Fig. 1. Worldwide production of photovoltaic modules between 2008-2009 and production planned between 2010-2012 [3]



	Australia	Canada	China	France	Germany	Greece	India	Israel	Italy	Japan	Poland	Russia	Spain	Switzerland	UK	USA	California
end 2007	83	25,8	100	76,2	3 862	9	112	2	120	1 919	0,64	0,2	855	31,4	18	831	301
end 2008	100		147	121,2	5 362	20		3	373	2 149	1,0		3 186			1 265	480

Fig. 2. Total capacity and yearly capacity increase of the installed PV systems in selected countries of the world in 2008 [7]

Knowledge of the possibilities of using photovoltaic systems and of their cooperation with power systems should be deepened and developed which can bring tangible effects in the future in the form of efficient diversification of energy supply sources.

1.1. Classification of photovoltaic systems

Photovoltaic systems can be classified according to different criteria. The most commonly applied criteria are as follows [1, 2, 4]:

- manufacturing technology (the construction material of the photovoltaic cells),
- location in relation to the surroundings,
- electric structure of the system,
- operation conditions in the general power supply system.

Photovoltaic cells can be classified into the following categories according to the manufacturing technology [2,4,]:

- monocrystalline: they are most often manufactured with the use of the Czochralski method, through drawing the monocrystalline growth from liquid boron-saturated silicon; the monocrystalline is most often formed into a cylinder which is then cut into 0,3mm thick plates (type p) with the radius of a few centimeters; next, the area of type n is formed in the thin surface layer through phosphorus diffusion, ,
- polycrystalline: the basic material used for the manufacturing is a silicon block with the weight of about 100kg, formed in the furnace as a result of melting and directed crystallization processes (with additives); the block is then divided into solids which are cut into 0,2mm thick square plates and polished at the same time after processing and selection; their efficiency is lower than the efficiency of cells made of monocrystalline silicon but the cost of manufacturing is considerably lower and it balances the ratio between the price of the modules and their efficiency,
- cells made of amorphous silicon: the manufacturing process involves applying thin layers onto glass, stainless steel or plastic; the manufacturing process is fast with low material consumption and easy automation; the efficiency of the cells is lower (and it lowers in the course of their exploitation) in comparison to the cells made of crystalline silicon but the cost of manufacturing them is lower,
- thin-film: the material that is most often used in the manufacturing process of those cells is hydrogenated amorphous silicon (most popular mainly due to its price), copper-indium diarsenide, cadmium sulphide or telluride and gallium arsenide (the most expensive material whose efficiency can reach up to 35%).

PV systems can be classified into the following categories according to the cooperation conditions with the general power supply system:

- systems connected to the electrical network (grid connected, on-grid): the first group contains solar power plants (commonly referred to as solar farms), in which all of the energy produced is resold to the grid; the second group includes PV installations whose basic task is providing load power supply, and in which the energy surplus is transmitted to the grid; in the cases when the PV system is not able to meet the needs, the whole energy shortage is absorbed from the grid,

– autonomous (stand alone, off-grid): stand-alone systems separated from public or local power networks used in the locations where other energy sources are not available or where the conversion of their energy into electricity would be more expensive than photovoltaic conversion; they supply, e.g. road signs, light and radio buoys for seaways, cathodic anti-corrosion protection of oil and gas mains, small household installations.

1.2. Photovoltaic systems in Poland

The solar industry market in Poland is still in the development phase and constitutes a marginal part among all the renewable energy sources. Currently, photovoltaic systems in Poland function as solutions of a didactic and demonstrative character, as well as power sources, for example, for monitoring stations, different types of signaling systems (e.g. marine), road signs, etc. [1]. Power production with the use of photovoltaic installations in Poland in comparison to other European Union member countries is presented on Fig. 3.

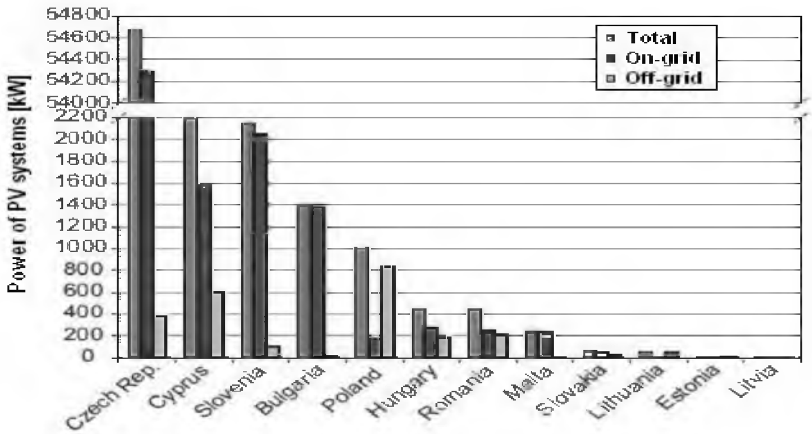


Fig. 3. Total installed capacity of photovoltaic systems in particular countries – new members of the European Union in 2008 [6]

The situation of Poland seems to be moderate in comparison to the countries mentioned above; however, it is worth noting the fact that, in contrast to other countries, autonomous installations have always been dominant in Poland which is still caused mainly by the legal and administrative barriers related to the network connection conditions (through treating PV installations almost equally to large power projects) and by the lack of appropriate financial support programs. What is more, also the purchase and sales price differences in national networks which are particularly unfavorable to small, independent producers of energy should be noted.

Considering all of the factors mentioned above, attention should now be paid to the need for education of qualified engineering staff in the field of installations using photovoltaic conversion, with particular focus on autonomous systems.

2. Battery charging controllers

The usable service life of a battery is strongly dependent on the way in which its charging and discharging is controlled, particularly in the case of lead-acid batteries. A good battery charging controller (regulator) limits the depth and the speed of discharge, appropriately for the battery temperature. In order to minimize the evaporation of the electrolyte, the controller also limits the charging voltage and the maximum charging level of the battery. The charging and discharging voltage limits should be set in such a way so as to correspond with the battery type and its operation temperature. The settings can considerably influence the maximum service life of the battery. High battery temperature can considerably shorten its service life as it accelerates corrosion and increases the self-discharging effect. High temperatures can also increase the gas emission during charging, which should be avoided, for example through forced ventilation of the battery box. In frosty temperatures, the service life of discharged lead-acid batteries is lowered. In relation to that, they should be charged well if they are to operate in low temperatures.

Photovoltaic modules used to charge batteries usually operate under direct current appropriate for the air temperature. Some charging controller use systems that track the maximum power point obtained from the module. The system automatically allows the module or the PV collector to operate under the voltage that guarantees maximum output power. They also provide protection against the so-called "dark" current drawn by the solar panel when there is no light if the panel is not equipped with a stop diode. The advantages resulting from the use of MPPT (maximum power point tracking) controllers depend on their application and their use should be considered taking into account additional costs and the risk of lower system reliability. For many applications, the operation of the module system at the set output voltage can be of equal or even higher economic effectiveness.

2.1. Types of controllers and their advantages

Two types of controllers can be distinguished:

- simple 1-2 stage – their operation involves pumping energy to the battery; after a certain voltage value is reached, the panel is disconnected,
- 3 stage PWM: e.g. Morningstar,
- MPPT – controllers tracking the maximum voltage point; this type of controllers operates also in a PWM mode; controllers of the MPPT type make it

possible to supply 10-30% more energy to the battery, they are usually more expensive than standard PWM controllers [8].

Solar PWM controllers use a technology similar to the one used in modern battery chargers. When the battery voltage reaches the set limit, the controller with the PWM algorithm enables slow reduction of the charging current in order to prevent battery overheating, at the same time trying to supply the maximum amount of energy to the battery in the shortest period of time possible. The operation of the PWM controller is based on pulse charging. Instead of providing constant energy supply to the battery, it sends short high voltage series. The controller checks the level of charging of the battery and determines how long the voltage series sent should be. If the battery is charged, the controller sends a short signal every few seconds, and if the battery is discharged, the signal is long and almost continuous [5, 9].

The PWM technology has also additional advantages, such as:

- the possibility of restoring the original battery capacity,
- the possibility of charging the battery up to 90-95% of its capacity in comparison to 60% for standard solutions,
- limiting the battery overheating process,
- automatic adjustment to the aging of the battery,
- control of voltage drops and temperature effects in photovoltaic systems.

Thanks to the advantages listed above, the following benefits can be obtained:

- longer service life,
- increased amount of the energy stored, and thereby the possibility of using a smaller battery in order to reduce the costs,
- lower PV system costs,
- lower frequency of device disconnection,
- 20%-30% more energy from the solar panels,
- the possibility to reduce the size of the PV system.

A new trend in the controllers cooperating with small photovoltaic sources that operate autonomously is the possibility of heating the battery chamber. When the ambient temperature is too low, the controller activates the heating system of the place where the battery is installed thanks to which its efficiency and service life increase at the cost of the energy that it stores. This type of solution is most frequently used in the systems in which the primary focus is put on reliable operation for as long as possible.

3. Test bench

In the laboratory testing, a miniature model of an off-grid system, which made it possible to perform measurements that can, for example, reflect the principle of operation of different types of charging controllers and of a system providing protection against deep discharge, was used. All the elements are used in physical battery charging systems that use the energy obtained from photocells.

The first experiment was conducted for a system constructed of a polycrystalline photocell, a charging controller (serial or shunt), condenser batteries, and a load point. The connection diagram of particular elements is presented on Fig.4. A semi-conductor set in the form of an electroluminescent diode of low wattage was used as the load point. After the system was connected, the solar module was lighted with a halogen lamp in such a way so that the initial voltage and current values were equal to $U_{condenser} \approx 4V$ and $I_{start} \approx 40mA$, respectively. The sampling of particular voltage and current measurements was performed with empirically determined frequency. The period between subsequent readings (20 or 40 seconds) depended on the speed with which the meter readings changed.

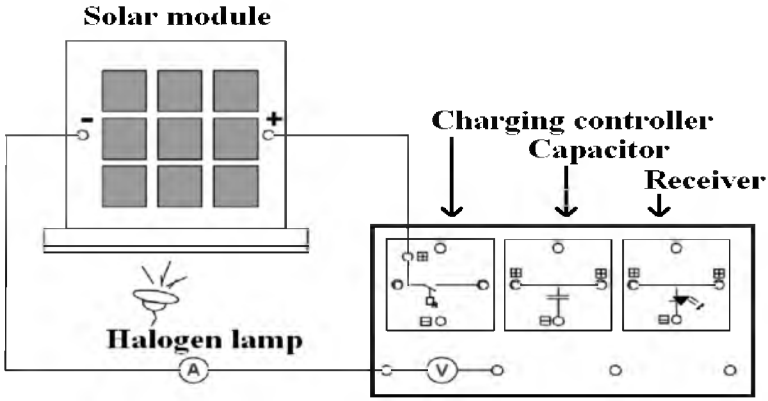


Fig. 4. The test diagram of a serial controller and of a shunt controller in an operation system with a solar module and a load point

Both controllers tested in that experiment are used in real systems to periodically charge the energy storage system. They are intended to disconnect the solar module from the condenser batteries if their voltage value is too high and to activate the system again to charge it when the value is too low. Such periodic operation at the correctly adjusted maximum and minimum voltage values makes it possible to extend the service life of the energy storage system. Two types of charging controllers can be distinguished according to the mode of operation:

- a shunt system; if the voltage value on the condenser is too low, the controller connects the solar module with the energy storage system and with the load point, which causes the charging process to start; when the voltage reaches the maximum value, the controller connects the solar module terminals through the appropriately adjusted resistance value which causes the load point to be powered only with the energy coming from the condensers;

– a serial system; if the voltage value on the condenser is too low, the controller connects the solar module with the energy storage system and with the load point, which causes the charging process to start; when the voltage reaches the maximum value, the controller disconnects the terminals causing the solar module to get disconnected from the system.

The second experiment aiming at protecting the system against too deep discharge was conducted in two stages. In the first stage, a system without protection was constructed, that is – similarly as it was done in the earlier experiment with the difference that a light bulb was used as the load point. Such a modification made it possible to increase the dynamics of the whole system, that is – its faster discharge. Additionally, it made it possible for the load point to draw more current than the value obtained from the solar module. Thanks to that, it was possible to go from the state of full charge to the voltage value below the deep discharge value in a short period of time. The voltage value of $U_{condenser} \approx 3V$ was assumed as the initial state when the measurements and the process of lighting the solar module with a halogen lamp were started.

The second stage involved conducting the same test with a module providing protection against deep discharge connected to the system. The connection diagram is presented on Fig. 5. The voltage and current values used in the previous example were maintained. The sampling of condenser voltage readings during the experiment was performed with the frequency of 10 seconds.

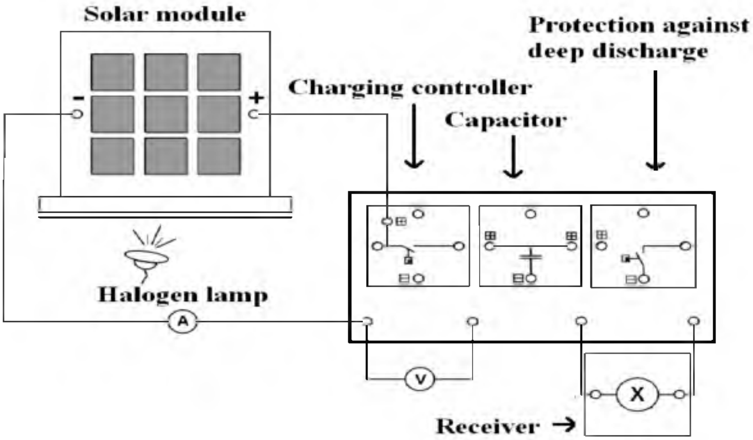


Fig. 5. The test diagram of a system with deep discharge protection

4. Experimental research

The off-grid power system model mentioned earlier which allows, among others, to perform the measurements of the charging voltage and current of condenser batteries from a photovoltaic source was used in the experimental testing. The modular construction of the system makes it possible to freely configure the connections and achieve different electric structures (PV module – load point, PV module – battery – load point). It is also possible to modify the parameters of particular sub-systems, such as: the value of the energy drawn by the load point (a semi-conductor system, an incandescent lamp, an asynchronous motor, potentiometers), the insolation of the photovoltaic cell (modification of the halogen lamp arrangement), and the controller type.

The first of the experiments involved testing a serial controller and a shunt controller under the same parameters set. The characteristics of the charging voltage of condenser batteries in relation to time for one operation cycle were determined, which is presented on Fig. 6. The characteristics confirm that the voltage value is kept between the values set regardless of the principle of operation of a particular controller. What is more, the characteristics of the power generated from a solar module in relation to time for the same operation cycle (Fig. 7) were determined. The diagram fully reflects the principle of operation of the controllers.

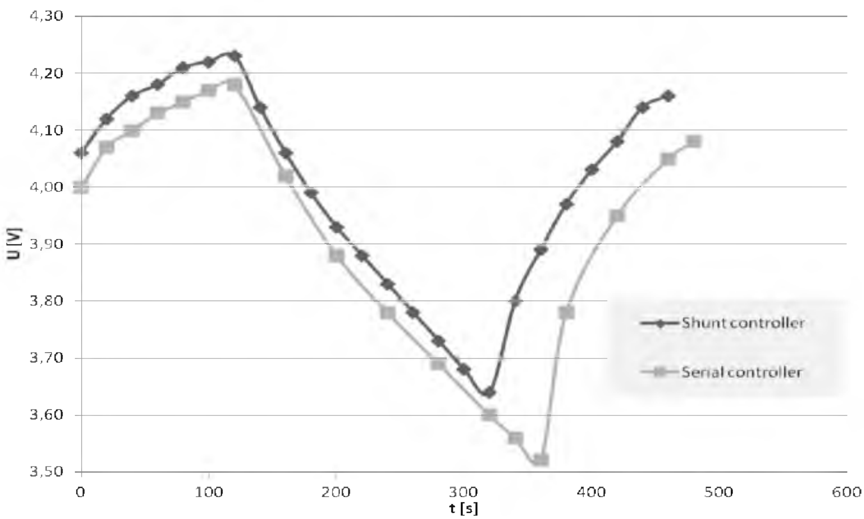


Fig. 6. Dependency between charging voltage of the condenser batteries and time for a system with a serial controller and with a shunt controller

The results of the second experiment connected with testing the deep discharge protection device are illustrated on Fig. 8. Comparing the voltage values for condenser batteries, it is possible to establish the level below which the circuit should not operate. What is more, it can be observed that the module responsible for emergency circuit cut-off operates under varying values of the activation and inactivation voltage of the load point.

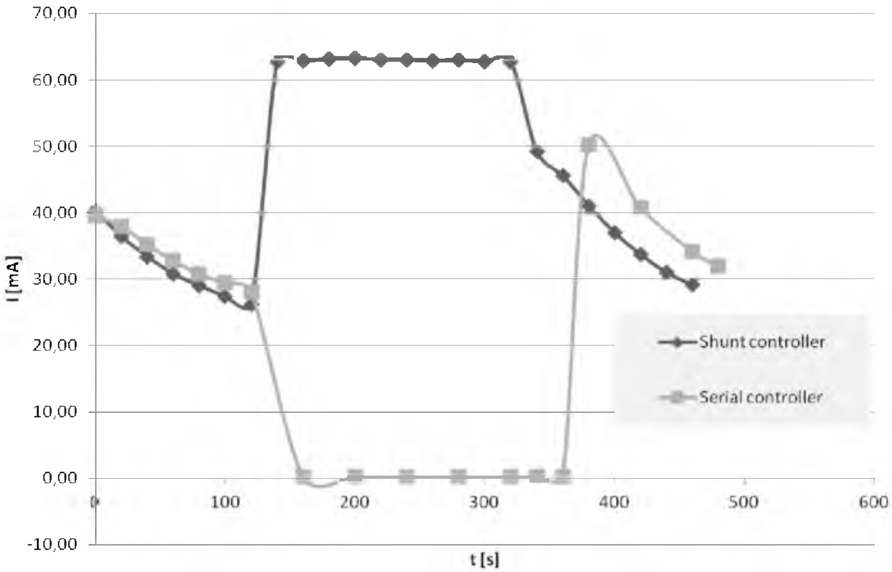


Fig. 7. Dependency between charging current of the condenser batteries and time for a system with a serial controller and with a shunt controller

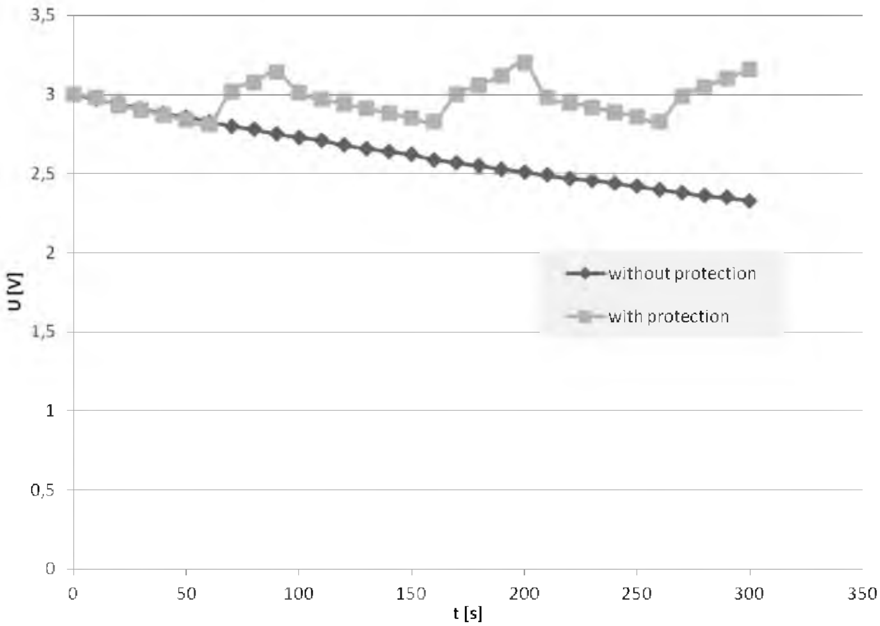


Fig. 8. Dependency between charging voltage of the condenser batteries and time for a system without a deep discharge protection device and for a system with such a device

5. Summary

It clearly results from the tests conducted that the main objective of using a condenser battery charging controller is maintaining the voltage at the set level that does not exceed either the minimal or the maximal value. Periodic recharging makes it possible to power the load point in a stable and continuous way. This is connected with cyclical, uniform, and in this way also more efficient operation of physical photovoltaic systems, in particular – those that operate in the off-grid system.

In emergency situations, when the controller is damaged and the charting voltage drops to the critical value, which can result in shorter service live or damage of the condenser batteries, the necessary element is a device providing protection against deep discharging. The device disconnects the power system of the load point till the voltage value returns to a safe level which protects the batteries.

The characteristics obtained clearly demonstrate the need to use charging controllers and deep discharge protection. Although establishing the exact construction of a photovoltaic off-grid power system requires consideration of many operation factors and parameters, the characteristics obtained in the laboratory indicate the general level of the advantages resulting from the introduction of those elements. The results obtained are intended to enrich the students' knowledge in the didactic process with regard to the basic principles applied in the design of autonomous photovoltaic systems.

References

[1] Butkowski M., Rynek technologii słonecznych w Polsce, PSE - Wschód Sp. z o.o., 2001.
[2] Jastrzębska G., Odnawialne źródła energii i pojazdy proekologiczne, Wyd. Naukowo-Techniczne, Warszawa, 2009.
[3] Jäger-Waldau A., PV Status Report 2011, DG Joint Research Centre, European Commission, Włochy, 2011.
[4] Klugmann-Radziemska E. Fotowoltaika w teorii i praktyce, Wydawnictwo BTC, Legionowo, 2010.
[5] Lipiński M., Pozyskiwanie energii elektrycznej ze słońca, *Wydawnictwo Instytutu GSMiE PAN, Kraków 1998*.
[6] Pietruszko S.M., Status of Photovoltaics 2008 in the European Union New Member States, Centre for Photovoltaics - Warsaw University of Techn., Warszawa, 2009.
[7] Pietruszko S.M., Światowy Rynek Fotowoltaiki, Centre for Photovoltaics - Warsaw University of Technology, Warszawa, 2009.
[8] Yu G., Jung Y., Choi J., Kim G., A novel two-mode MPPT control algorithm based on comparative study of existing algorithms, *Solar Energy 76 (2004)*.
[9] http://greenworld.serwus.pl/Ogniwa/efekt.htm, *Systemy i budowa*, 10.11.2012.