

Research paper

A methodology for the construction of efficient PLC based low-power photovoltaic generation plants

A.A. Shilin *, F.V. Savrasov, A.P. Kriger

Tomsk Polytechnic University, Russian Federation

Received 15 March 2016; received in revised form 22 June 2016; accepted 25 June 2016

Available online 16 September 2016

Abstract

The research of the operation of low-power photovoltaic generation plants used for self-contained electric power supply in Siberian climatic conditions is performed in this paper. It provides an analysis of the operation of individual units of an automated control system, and gives recommendations for the selection of hardware components. The article describes the operational principles, developed based on functional modules of the programmable logic controller, ensuring maximum possible use of solar energy in this continuous power supply system. The results of plant operation have been obtained, in the form of a power counter log, as well as data on the volume of solar energy produced in both overcast and in sunny weather, throughout the observation period. The article provides visual illustration of generated energy, which could be used to assess the efficiency and economic viability of the low-power photovoltaic plant. Authors would like to point out that examples of the proposed methodology for the construction of self-contained power supply systems can be found in existing industrial facilities, on which further scientific research can be based.

© 2016 Tomsk Polytechnic University. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Keywords: Autonomous power generation systems; PLC; MPPT; PV; Battery; PWM; FBD; Charge control switch; Adapter circuit

1. Introduction

The process of the development of autonomous electric power supply systems, based on photovoltaic panels, is hindered by problems related to the selection of the best equipment, which has to ensure the most efficient use of solar power as well as the automatic switching to backup supply [1–3]. The need to use modern technologies ensuring the most efficient exploitation of solar energy, as well as providing crucial functions required for various equipment, places considerable limitations on the possibility of using more complex and effective solutions. The present article describes a fully fledged system with a single programmable controller, allowing for various subsequent upgrades by developers, as well as for further research. In particular, the proposed solution brings together the concept of efficient exploitation of solar energy, and the best choice of power source, in a single controller. Indeed, the proposed structure can also prove useful in research and the

performance of other tasks, not envisaged by the present article. As an example, authors can consider the technology used to optimise the charging and discharging cycle of a battery, whilst also ensuring the process' reliance on solar energy as much as possible. However, authors note that, presently, that research is dedicated to the optimisation of the selection of equipment and its concurrent operation with the plant's other systems. The relevance of such a development is further emphasised by the demand for autonomous low-power systems in those regions of the Russian Federation, where it is either impossible or unjustifiably expensive to rely on the central supply system. Such areas include smaller towns in Yakutia, Buryatia, as well as some foreign territories (Mongolia and others), where the weather is mostly sunny, both in winter and in summer. The subject of our research is an autonomous power supply system, with automatic switching to one of three available backup power sources, lined up by priority:

- 1 Inverter of continuous power from a DC battery, into alternate current.
- 2 External power supply.
- 3 Power generator based on the internal combustion engine (petrol generator).

* Corresponding author. Tomsk Polytechnic University, Russian Federation.
Fax: +7 (3822) 400 887.

E-mail address: shilin@tpu.ru (A.A. Shilin).

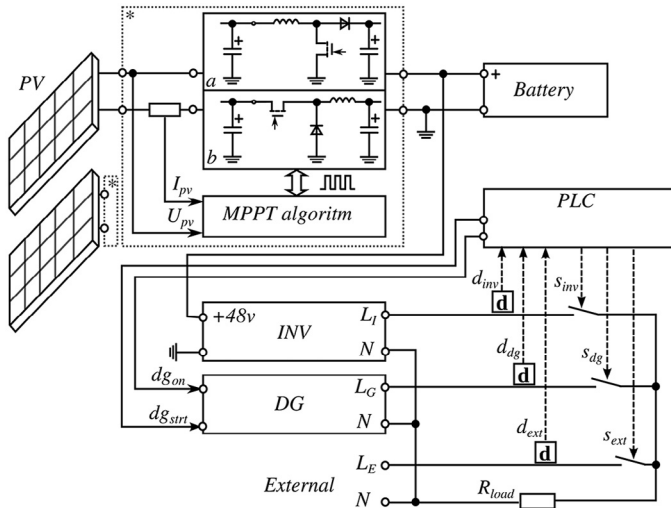


Fig. 1. A functional diagram of the autonomous power system.

A functional diagram of a standard autonomous system is provided in Fig. 1, where the following indications are used: PV, photovoltaic panel; MPPT, a controller capable of locating the maximum power point, operating on one of two possible types of switch-mode transformer; PLC, programmable logic controller; INV, inverter; DG, diesel or petrol generator. Relay circuit for automatic switching to backup power source, including a source detection sensor on three sources (d_{inv} , d_{ext} , d_{dg}) and the corresponding actuators (s_{inv} , s_{ext} , s_{dg}). Battery is a rechargeable battery.

Optimal use of solar energy is ensured by the MPPT battery charge controller, coordinating the supply of energy to the inverter. Industrial MPPT units include functions, such as over-charge protection, charging rate correction, etc. However, several additional functions are also required by autonomous systems, ensuring economic management of the electric power whilst reducing the cost of maintenance [4]. On such an effective and universal device is the programmable logic controller, which can perform a range of tasks, formulated as algorithms [5–7]. Here are some of the functions not normally covered by common MPPT controllers:

- 1 Automatic selection of power source based on a pre-set priority order, giving preference to the lowest unit price for energy (kWh).
- 2 The launch and the turning off of the fuel power generator, including several operational modes and interim checking cycles.
- 3 The activation and deactivation of the inverter (increasingly relevant as the use of an inverter in circumstances where there is no charge is important in low-power autonomous systems).
- 4 Monitoring and management of charging and discharging cycles of batteries during operation.

Performance of these tasks is not a problem where PLC is used; similar features are being offered by various manufacturers [8]. The issue, however, is the maintenance of the efficiency of MPPT controllers and PLC devices in low-power systems [9].

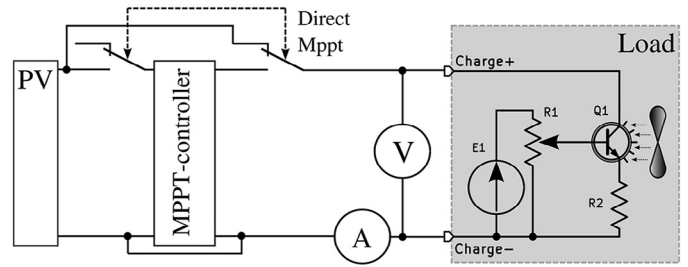


Fig. 2. Functional diagram of the experimental structure.

2. Procedure of experiment

The assessment of the viability of MPPT controllers relies on the ratio between the energy passed to the battery (with or without the controller) and that consumed by an industrial MPPT controller [10]. This ratio can be calculated based on the following formula

$$k_e = \frac{U_{akk} \cdot I_{akk1} - P_{mppt}}{U_{akk} \cdot I_{akk2}} \quad (1)$$

where U_{akk} is the battery voltage; I_{akk1} , I_{akk2} is the charging current with or without the use of an MPPT, P_{mppt} is the power used by the controller.

An example of this principle has been addressed by authors in Kaftanchikovo Tomsk region, which described an experiment involving the construction of an autonomous system, with the view to provide evidence of this efficiency ratio k_e .

Fig. 2 shows a functional diagram of the autonomous system, on which experiments were conducted, where a regulated charge simulator was used instead of a battery. The results of measurements, in different weather conditions, are indicated in Table 1.

As demonstrated in Table 1 a low effectiveness of MPPT controllers (the ratio is lower than one) is clearest in overcast weather conditions, where the battery charge is at its highest: ($U_{akk} > 51V$). In such circumstances, the power used by the controller exceeds the difference between the power outputs of the two researched systems (both with or without the controller).

In order to assess the effectiveness of the use of controllers in more detail, we can examine the current–voltage ranges $I_{pv}(U_{pv})$, obtained through experiments, described previously, in various lighting conditions in which the photovoltaic (solar) panes were operating. Fig. 3 shows the characteristics, along with the power curves P_{pv} where, on the curves showing the three typical weather conditions, corresponding operational modes of the battery are indicated in grey.

Sections where the peak power is reached in sunny (Fig. 4), partially cloudy (Fig. 5) and overcast (Fig. 6) weather are indicated in a separate drawing.

Table 1
The results of measurements of the efficiency ratio (1).

U_{akk}, V	Overcast	Intermittent clouding	Sunny
45.0	1.16	1.07	1.06
49.0	0.97	0	1.02
53.0	0.93	0.97	0.98
57.0	0.95	0.98	1.01

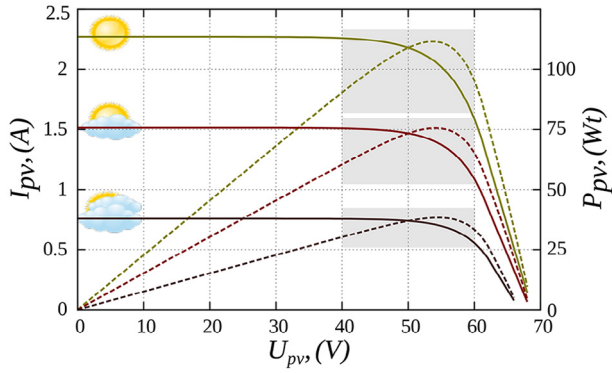


Fig. 3. The range of current-voltage ratios.

As indicated in Figs. 4–6, an efficiency ratio higher than one is only possible in sunny weather conditions, with low battery charge or by reducing MPPT controller consumption, through intensified research of operation of other controllers. This is indirectly confirmed by the studies described in Ref. [11].

Similar problems are encountered with PLC, due to the fact that only universal types of PLC are available on the market, with various functions (in some cases exaggerated) and using other equipment which, in the context of low-power systems, are just too dependent on energy.

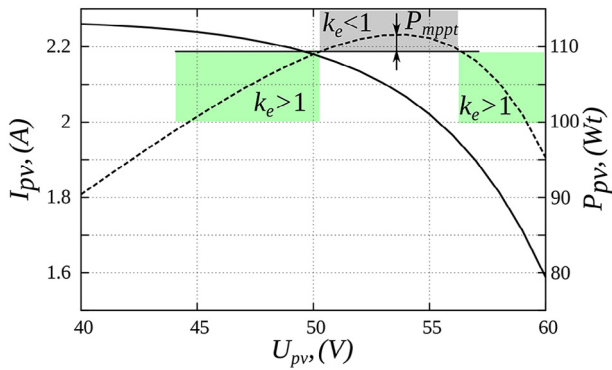


Fig. 4. The voltage ratio under intensive direct insolation (averaged value is 980 Wt/m^2).

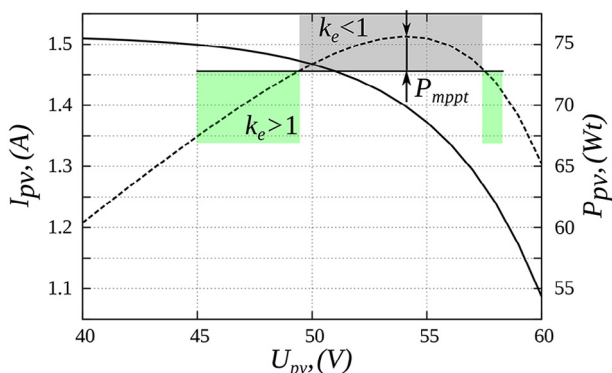


Fig. 5. The voltage ratio at limited cloudiness (averaged value is 659 Wt/m^2).

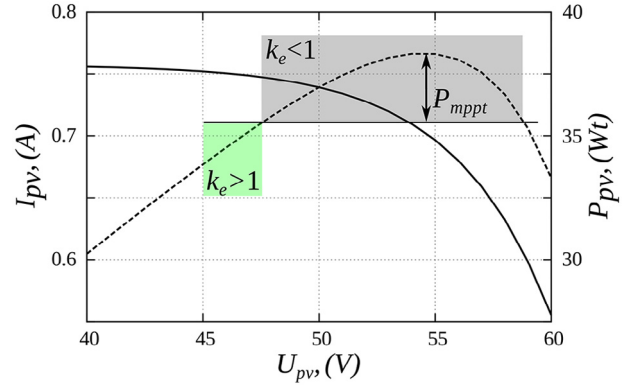


Fig. 6. The voltage ratio at extensive cloudiness (averaged value is 278 Wt/m^2).

The choice of a PLC in autonomous systems relies on the device’s functional ability to operate independently, based on (its own) programming structure, such as the well-known MPPT algorithm, referred to in the literature [12,13]. With this in mind, authors would be looking for new control and operational components for PLC interaction [14].

3. Methodology of selection of suitable components and algorithms and its description

In order for the MPPT-algorithm to work in conjunction with the PLC, a sensor has to be added to the PLC, to monitor the current and the voltage of photovoltaic (solar) panels, assisted by an AD converter, all controlled by a PWM providing a key switching point in current management. Fig. 7 illustrates a simplified adapter circuit based on autonomous system components, with peripheral PLC nodes, where current measurement function is performed by the operating amplifier U1.

Division devices, composed of R_8 and R_7 , ensure voltage matching and in-line voltage references for the PLC ADC. In particular, in order to measure the voltage in values up to 64V, the resistance offered by the division device can easily be calculated, based on the formula:

$$R_8 = \frac{R_7 \cdot U_{maxpv}}{U_{adc}} - R_7 \quad (2)$$

The value of resistance in current measuring devices can be calculated based on the following equation:

$$U_{out} = \frac{R_6}{R_1} \cdot I_{pv} \cdot R_3, \quad R_1 = R_2 = R_4 = R_5. \quad (3)$$

The charge control switch is configured based on the structure of switch-mode power supply controlled by a PWM. The calculation of required specifications for diode D_1 and choke L_1 can be made based on existing methods. In particular, based on the set frequency f_{pwm} the PWM controller can calculate the inductiveness of choke based on the following formula:

$$L_1 = (V_{PVmax} - V_{Amin}) \cdot \frac{V_{Amax}}{V_{PVmin}} \cdot \frac{1}{f_{pwm}} \cdot \frac{1}{I_{IR}} \cdot \Delta I_{Amax}, \quad (4)$$

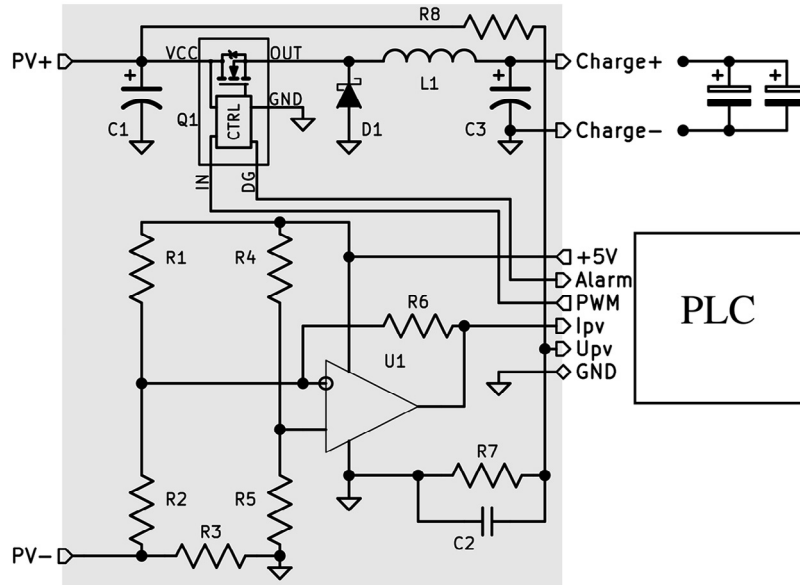


Fig. 7. The principle of harmonisation of the autonomous system and its peripheral PLC nodes.

where V_{PVmin} and V_{PVmax} are the minimum and maximum loads on photovoltaic (solar) panel, V_{Amin} and V_{Amax} are the minimum and maximum loads on the batteries, $I_{IR} = 0.3$, ΔI_{Amax} the maximum allowed amplitude of current alteration on the choke. A more detailed description of key switch components can be obtained from the texts on microcircuits used in step-down devices for switch-mode power supplies [15]. One such method (approach), aimed at reducing power consumption by individual system devices, is to use modern switching circuits, controlled by an optothyristor, as part of the automatic backup power selection system.

The backup switching principle has to be carefully designed, considering inertia processes which occur at the time of activation and deactivation. The same algorithms can be applied to PLC.

Once a design solution has been selected, what remains to be found is a suitable programmable controller capable of providing the functions described above. A large number of different PLC available on the market covers almost all requirements of the developer; however, the limited power consumption forces the developer to base his choice on cheap controllers, based on low-consumption microprocessors. As a rule, such PLC do not support conventional operating and programming environments (such as Ref. [16]) and require dedicated programming support in low-level languages, making the task of implementing the methods researched much more complex. Nevertheless, some solutions for controllers do exist (such as STM32F1) whose programming environment are compatible with modelling principles supported by SciLab Xcos [17]. A distinguishing feature of such PLC is the limited number of functional units, which can be used for development, research and modelling purposes. Indeed, this limited number of functional units still allows us to produce working solutions.

There are several types of MPPT-algorithms, to be contained in the programmes, developed based on the following equations [18–23]. All algorithms considered here are based on the calculation of partial derivatives, obtained from measurements of

current and voltage, with finite level quantisation steps, important for the 10–12 bit AD converter step, itself level-quantified which, in terms of the design of a low-power PLC, is liable to cause problems with the stability and accuracy of algorithm data. The analysis of several existing systems, aimed at finding the optimal charge by photovoltaic panels, leads the authors to select the method based on locating the optimal charge point, which does not rely on the measurement of derivatives. The method is based on the alternate operation of charging systems based on two values, set by the PWM, which are illustrated in Fig. 8.

Considering the power in two points, in individual sections of the power curve, authors observe that the optimal (maximum) consumption of energy occurs in the conditions of equity P_i and P_{i+1} , where $P_i \rightarrow P_{i+1}$. Achievement of power equity is the only solution since there is only one highest power point, and since that point cannot be situated at the end of the value range k_{pwm} . Furthermore, the difference in power value ΔP can be considered as the value of deviation in $e(k_{pwm})$ the enclosed regulation contour with PWM k_{pwm} . Visual illustration of the maximum transmission ratio is given in the figure.

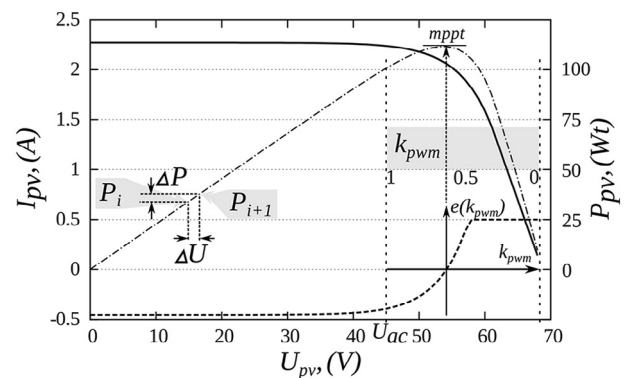


Fig. 8. The method based on two PWM operational values.

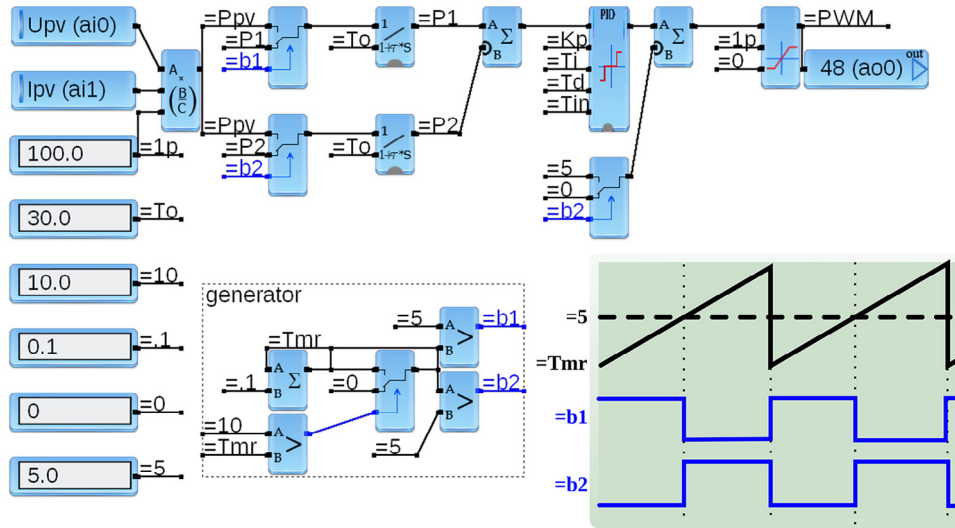


Fig. 9. MPPT algorithm, based on functional units (FBD).

Authors demonstrate that the indicated algorithm can be implemented in PLC based on a limited platform (Fig. 9). As examples of limited platform PLC, authors consider the VEST [24], based on STM32F101 processes, capable of executing FBD scripts on 8 MHz processors, with a digitisation rate of 100 ms, where the power consumption of PLC, based on a 24 V source, does not exceed 4 mA.

An important feature of this approach is the inertia of the measurement procedure in the functional unit environment, where the assessment is based on average power values P_1 and P_2 several time intervals. The time average constant must be higher than the selected time period reserved for the measurement of power (10 sec) by at least three times. In this way, the mathematical model set by the PID controller can be expressed in operating form, as follows:

$$W_{ob}(s) = \frac{E(s)}{P_1(s) - P_2(s)} = \frac{k_{Imax}}{(1 + 10 \cdot s) \cdot (1 + 30 \cdot s)} \quad (5)$$

The transmission ratio at the point of equity depends on the intensity of radiation of the PV; indeed this dependence has a continuous character. Consequently, reliable operation will only require optimum settings to achieve the peak value [25]. The parameters on which the PID controller ratios are defining can

be calculated by making them consistent with their characteristic reference equations corresponding to fourth-order pass of the Butterworth filter, or by other methods [26]. The following values are used for operation of object (5)

$$k_p = 1.2, \quad T_d = 28, \quad T_i = 38, \quad (6)$$

in order to secure continuous operation of the closed-loop MPPT-algorithm.

4. Conclusions

The results of the operation of the autonomous low-power photovoltaic generation plant considered here are indicated as power meter logs, measuring the output of the electric power inverter. A 150 w tungsten lamp was used as the load for the inverter. Furthermore, Fig. 10 illustrates the estimated and the real degree of generation of electric power by photovoltaic transformation. The difference in energy generated by the PV and that consumed by the inverter largely determine the inverter's efficiency ratio (estimated at 82. .86%), as well as the error in the measurement of power by PLC. Furthermore, the amount of energy consumption by the PLC does not exceed 1 W, compared to the consumption of MPPT controllers (15 W).

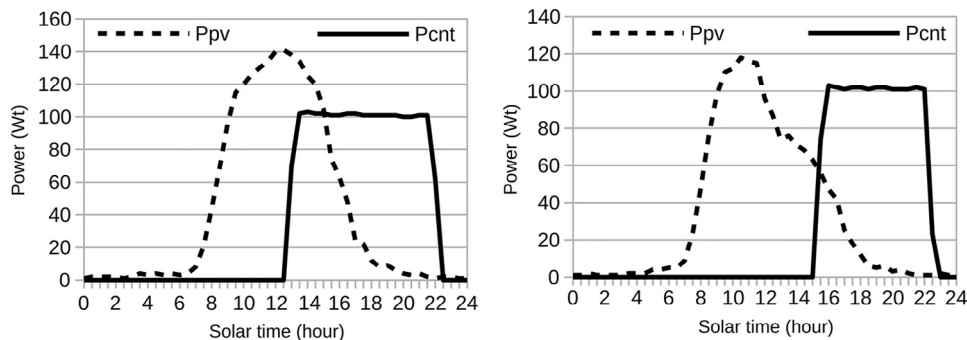


Fig. 10. The logs of energy generated by solar panels Ppv and by inverter $Pcnt$.

An accurate calculation of the pay-off time of the proposed autonomous low-power photovoltaic generation plant can only be made where construction of a more powerful autonomous plant is not justified due to climatic conditions in the area of exploitation. As a rule, the cost of power generation in such regions is considerable. As an example, in remote towns of Yakutia, where electric power is only produced by petrol generators, and where the number of consumers is limited to ten, the cost of one kW of electric power is USD 1.20. In such circumstances the cost of building an autonomous power plant could be repaid after two years of exploitation.

Construction of efficient autonomous low-power generation systems, based on photovoltaic (solar) energy, requires not only a solution for the problem of unsatisfactory operating principles of MPPT-controllers, but also a careful examination of compatibility of the components used in the structure of PLC controllers. A poor choice of components can lead to a considerable reduction of effectiveness of MPPT controllers. This article proposes a wider outlook on this issue, looking beyond the limits set by algorithms and methods, focusing on individual, optimal design of both battery charging systems and the manner of providing a continuous power supply. The outcome of resolving these issues was the new design and building approaches for MPPT-algorithm, based on functional PLC units. The results of this research have allowed us to build several working sample autonomous plants, which are currently operational in towns of Yakutia. One of them is being used as an active example, in other research. One of the results achieved through implementation of the described solutions was a significant reduction in power consumption by autonomous plant control systems. Experimental research demonstrated the effectiveness of autonomous systems, even in adverse weather conditions in late autumn (October) in an area where the overall solar activity is lower than those recommended for such exploitation. The experiments allowed us to gather information about solar energy which allowed to calculate the pay-off period in the regions of implementation.

References

- [1] G. Lazaroiu, M. Longo, M. Roscia, M. Pagano, Comparative analysis of fixed and sun tracking low power PV systems considering energy consumption, *Energy Convers. Manag.* 92 (2015) 143–148, doi:10.1016/j.enconman.2014.12.046.
- [2] M. Meral, F. Diner, A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems, *Renew. Sustain. Energy Rev.* 15 (5) (2011) 2176–2184, doi:10.1016/j.rser.2011.01.010.
- [3] B. Huang, M. Wu, P. Hsu, J. Chen, K. Chen, Development of high-performance solar led lighting system, *Energy Convers. Manag.* 51 (8) (2010) 1669–1675, doi:10.1016/j.enconman.2009.11.046.
- [4] A. Mohammed, J. Pasupuleti, T. Khatib, W. Elmenreich, A review of process and operational system control of hybrid photovoltaic/diesel generator systems, *Renew. Sustain. Energy Rev.* 44 (2015) 436–446, doi:10.1016/j.rser.2014.12.035.
- [5] F. Guerin, D. Lefebvre, V. Loisel, Supervisory control design for systems of multiple sources of energy, *Control Eng. Pract.* 20 (12) (2012) 1310–1324, doi:10.1016/j.conengprac.2012.07.006.
- [6] M. Fuentes, M. Vivar, J. Burgos, J. Aguilera, J. Vacas, Design of an accurate, low-cost autonomous data logger for PV system monitoring using Arduino that complies with IEC standards, *Sol. Energy Mat. Sol. Cells* 130 (2014) 529–543, doi:10.1016/j.solmat.2014.08.008.
- [7] A. Pernia, J. Arias, M. Prieto, J. Martinez, A modular strategy for isolated photovoltaic systems based on microcontroller, *Renew Energy* 34 (7) (2009) 1825–1832, doi:10.1016/j.renene.2008.11.026.
- [8] E. Irmak, N. Guler, Application of a high efficient voltage regulation system with MPPT algorithm, *Int. J. Elec. Power Energy Syst.* 44 (1) (2013) 703–712, doi:10.1016/j.ijepes.2012.08.011.
- [9] Z. Zhou, P. Holland, P. Iqic, MPPT algorithm test on a photovoltaic emulating system constructed by a dc power supply and an indoor solar panel, *Energy Convers. Manag.* 85 (2014) 460–469, doi:10.1016/j.enconman.2014.06.007.
- [10] W. Chen, H. Shen, B. Shu, H. Qin, T. Deng, Evaluation of performance of MPPT devices in PV systems with storage batteries, *Renew Energy* 32 (9) (2007) 1611–1622, doi:10.1016/j.renene.2006.06.009.
- [11] R. Faranda, S. Leva, Energy comparison of MPPT techniques for PV systems, *WSEAS Trans. Power Syst.* 3 (6) (2008) 446–455.
- [12] A.E. Mohamed, Z. Zhengming, MPPT techniques for photovoltaic applications, *Renew. Sustain. Energy Rev.* 25 (2013) 793–813, doi:10.1016/j.rser.2013.05.022 <<http://www.sciencedirect.com/science/article/pii/S1364032113003250>>.
- [13] S. Lyden, M. Haque, Maximum power point tracking techniques for photovoltaic systems: a comprehensive review and comparative analysis, *Renew. Sustain. Energy Rev.* 52 (2015) 1504–1518, doi:10.1016/j.rser.2015.07.172 <<http://www.sciencedirect.com/science/article/pii/S1364032115008199>>.
- [14] J. Fernandez-Ramos, L. Narvarte-Fernandez, F. Poza-Saura, Improvement of photovoltaic pumping systems based on standard frequency converters by means of programmable logic controllers, *Sol. Energy* 84 (1) (2010) 101–109, doi:10.1016/j.solener.2009.10.013.
- [15] M. Wens, M. Steyaert, Design and Implementation of Fully-Integrated Inductive DC-DC Converters in Standard CMOS, Springer, Berlin, Germany, 2011, doi:10.1007/978-94-007-1436-6. ISBN 978-94-007-1435-9.
- [16] CoDeSys, The complete software suite for automation technology, <<http://www.codesys.com>>; 3S-Smart Software Solutions GmbH (accessed 22.06.16).
- [17] Scilab, Open source software for numerical computation, <<http://www.scilab.org>>; Scilab Enterprises S.A.S. (accessed 22.06.16).
- [18] K. Itako, T. Mori, A current sensorless MPPT control method for a stand-alone-type PV generation system, *Electr. Eng. Jpn.* 157 (2) (2006) 65–71, doi:10.1002/ej.20424 (English translation of Denki Gakkai Ronbunshi).
- [19] J. Ma, K. Man, T. Ting, N. Zhang, S. Guan, P. Wong, et al., Improving power-conversion efficiency via a hybrid MPPT approach for photovoltaic systems, *Elektron. Elektrotech.* 19 (7) (2013) 57–60, doi:10.5755/j01.eee.19.7.5163.
- [20] Y. Yongchang, Y. Chuanan, Implementation of a MPPT controller based on AVR mega16 for photovoltaic systems, *Energy Procedia* 17 (Pt A) (2012) 241–248, doi:10.1016/j.egypro.2012.02.090 <<http://www.sciencedirect.com/science/article/pii/S1876610212004262>> 2012 International Conference on Future Electrical Power and Energy System.
- [21] L. Fialho, R. Melicio, V. Mendes, A. Estanteiro, M. Collares-Pereira, PV systems linked to the grid: parameter identification with a heuristic procedure, *Sust. Energy. Tech. Assess.* 10 (2015) 29–39, doi:10.1016/j.seta.2015.01.006.
- [22] F. Chekired, A. Mellit, S. Kalogirou, C. Larbes, Intelligent maximum power point trackers for photovoltaic applications using FPGA chip: a comparative study, *Sol. Energy* 101 (2014) 83–99, doi:10.1016/j.solener.2013.12.026.
- [23] A. Dolara, G.C. Lazaroiu, S. Leva, G. Manzolini, Experimental investigation of partial shading scenarios on PV (photovoltaic) modules, *Energy* 55 (2013) 466–475, doi:10.1016/j.energy.2013.04.009.
- [24] Akiar, Programmable logic controller west-02, <<http://npwest.ru/index.php/produksiya/programmiruemye-logicheskie-kontrollery>>; LLC NPO VEST (accessed 22.06.16).
- [25] H.K. Khalil, *Nonlinear Systems*, third ed., Prentice Hall, Upper Saddle River, NJ, 2002. ISBN 0-13-067389-7.
- [26] J. Shen, H. Chiang, PID tuning rules for second order systems, in: 5th Asian Control Conference, vol. 1, 2004, pp. 472–477.