COMPUTATIONAL PROBLEMS OF ELECTRICAL ENGINEERING

Vol. 13, No. 2, 2023

SIMULATION MODELING OF A POWER SUPPLY SYSTEM TAKING INTO ACCOUNT THE STOCHASTIC NATURE OF ENERGY GENERATION AND CONSUMPTION PROCESSES

Kateryna Klen, Vitalii Navrotskyi, Valery Zhuikov

National Technical University of Ukraine "Igor Sikrosky Kyiv Polytechnic Institute", Kyiv, Ukraine

ekateryna.osypenko@gmail.com, prefac@ukr.net, valery.zhuikov@gmail.com

https://doi.org/10.23939/jcpee2023.02.

Abstract: This paper presents the calculation of parameters and simulation modeling of the power supply system based on solar panels, taking into account the stochastic nature of the processes of energy generation and consumption. Through simulation in MATLAB® Simulink, the performance of the power supply system under the change of solar insolation and load power was evaluated. The method of controlling a bidirectional converter based on the calculation of the difference in Shannon entropy of energy generation and consumption flows is described. This method allows for increasing the efficiency of energy use in the system by reducing the difference between the entropy values at the input and output of the system. It also allows for reducing the duration of time intervals when the energy storage in the system is uncontrollable while being fully charged or fully discharged. Modeling of electrical processes in the power supply system was carried out with the implementing the control either considering the entropy difference or without it. To evaluate the impact of the accuracy of determining the entropy values on the modeling results, the entropy for different interval durations was calculated. The results of modeling the power supply system were analyzed using solar insolation and load power data with a 1-minute discreteness.

Key words: power supply system, solar panel, energy storage, Shannon entropy, MATLAB® Simulink.

1. Introduction

The development of solar energy and other renewable energy sources is an important step towards creating a sustainable and resilient energy future. In 2022, the installed capacity of solar power plants increased to 773 GW, and the total capacity of renewable energy sources reached 2.7 TW [1, 2]. Solar energy is the fastest growing segment of renewable energy and is projected to increase to 2.4 TW by 2026 [3].

Investments in renewable energy sources have become a key factor in ensuring sustainable development and combating climate change. In 2019, investments in renewable energy reached a record level, exceeding USD 4.5 trillion by 2050, taking into account investments in new solar power plants, their reconstruction and modernization [4].

A Green tariff is an important tool for stimulating the development of renewable energy in Ukraine. A feed-in tariff is a special price rate that guarantees free transmission to the grid and a fixed price for each kilowatt-hour of energy produced using renewable sources [5].

One of the peculiarities of renewable energy sources is the variable and probabilistic nature of their output power, which significantly depends on environmental conditions. The presence of an electric energy storage device in power supply systems ensures not only the realization of the extraction of maximum energy from renewable sources by fulfilling the condition of equality of the internal resistance of the equivalent source and the load resistance, compensation for uneven primary energy flows, but also the balance of the power output of renewable energy sources and the load power. The construction of control systems intended for ensuring the efficient operation of power supply systems with renewable energy sources can provide the determination of the entropy characteristics of the energy generation processes, as well as the consumption and formation of control influences based on their calculation [6]. To achieve efficient utilization of the energy storage system, it is necessary to develop a control unit for the solar-powered energy system using the entropy analysis.

The study of the control system including the use of calculated entropy is highly innovative. However, there are works devoted to the issue of predicting load power using the entropy calculations [7]. Another publication on a similar topic [8] describes the use of entropy for the analysis of generation processes in the system. These publications clearly show that the problem of using entropy in the data analysis remains relevant.

The purpose of this paper is to describe the process of developing a control system for solar cell-based power supply using the entropy analysis, which will allow the efficient use of the energy storage.

2. Block diagram of the power supply system

The power supply system based on a solar battery with energy storage consists of the following elements (Fig. 1):

1) PV is a solar cell [9], represented by an equivalent current source J and an internal resistance Rpv;

2) DC-DC is a step-up pulse width converter [10, 11], which ensures the operation of the solar battery in the mode of maximum energy extraction;

3) Load is a load represented by a variable resistor;

4) Bidirectional DC-DC is a bidirectional converter [12, 13], which is a charging and discharging device for a storage device;

5) Battery is a storage device [14, 15] that balances energy in the system.

The system also has a control unit [16] that takes into account the stochastic nature of the processes of generating and consuming electricity and ensures the efficient operation of the storage device.

In order to model the electromagnetic processes in this system, first it is necessary to develop a model that takes into account the features of distributed generation with the storage, as well as system control mechanisms.

3. Modeling of electromagnetic processes in the power supply system

To conduct the computer study of electromagnetic processes in the power supply system with a storage device, a model was developed in the Matlab R2023a Simulink environment that implements simulation modeling of systems using graphical blocks with specified parameters [17]. The diagram of the model of the solar power system is shown in Fig. 2. The model contains the following elements:

- PV Array is a photovoltaic module [18] that allows for emulating the operation of solar panels;
- IGBT is a transistor;
- Diode is a semiconductor diode;
- L1 = 10 mH, L2 = 90 mH are inductors;
- C1 = 5 mF, C2 = 180 mF, C3 = 1200 μF, C4 = 1200 μF are capacitors;
- Load is a subsystem of adaptive variable load;
- PWM is a PWM signal subsystem that controls the step-up converter;
- inputdata.mat, powerdata2.mat are blocks for loading data from external files [19];
- Battery is a 150 Ah lithium-ion battery [20];
- IGBT/Diode, IGBT/Diode2 are transistors responsible for the efficient control of the energy transfer between the solar panel, the storage device, and the load.

To simulate the system, the real insolation data from the LARES laboratory in Zagreb, Croatia [21] and household electricity consumption data [22] are used, both sets of data having a discreteness of 1 minute. Due to their fluctuations, there is a change in the power of generation and consumption [23], which in turn affects the change in entropy. The difference between these entropy values is then found. Depending on the sign of the obtained result, the direction of the energy flow through the bidirectional converter is established.

Due to technical limitations of the modeling, the time intervals were converted from 1 minute to 0.1 second of the model. Some of the conversion results are shown in Table.

Insolation and power consumption values with a 1-minute discreteness

Time	Power of the solar panels	Load capacity	Modeling time
12:50:00	7404	1404	77
12:51:00	7361	1406	77.1
12:52:00	7336	1394	77.2
12:53:00	7252	1404	77.3
12:54:00	7168	1400	77.4
12:55:00	7195	1384	77.5
12:56:00	7186	1332	77.6
12:57:00	7274	1338	77.7
12:58:00	7269	1334	77.8
12:59:00	7028	1334	77.9
13:00:00	4846	1326	78
13:01:00	3807	1334	78.1
13:02:00	6680	1338	78.2

Since the variable resistor [24] from the MATLAB Simulink library containing a built-in DC power supply does not meet the needs of the model, an adaptive variable load unit was developed. This block consists of 10 resistors which are controlled as follows: the control system automatically turns on or off individual resistors, depending on the power consumption. Logical conditions are used to determine the number of 10-ohm and 2.5-ohm resistors that need to be connected to achieve the desired resistance determined by the following equation:

$$R = round\left(220^2 / P / 2{,}5\right) \cdot 2{,}5 . \qquad (1)$$

The described method makes it possible to automatically adjust the load according to the current power value, which allows for studying various scenarios of load changes, taking into account the stochastic nature of the processes in the system.

This model of the power supply system, the data on the entropy change of generation and consumption, as well as the method of controlling the change of the resistor are the basis for developing a method of controlling the charge-discharge device.

4. Implementation of charge-discharge device control based on the calculation of the entropy difference

The control system of a bidirectional converter, which is a storage charger, consists of developed blocks for entropy calculation (Fig. 3, a) and a control unit (Fig. 3, b), which includes three subsystems:

The first subsystem determines the energy storage current which provides the voltage value at a load of 220 V. The operating range of currents is from -50 A to 50 A and depends on the difference between the measured and current load voltages. This difference is converted into a fill factor using a Proportional-Integral (PI) controller [25].

The second subsystem generates pulse-width modulation (PWM) signals [26]. Its function is to compare the measured drive current with the current value received from the first subsystem. The difference between these values is converted into a sequence of current pulses with a certain fill factor using a PI controller. These values are then compared with the sawtooth signal from the Sawtooth unit and fed to the third subsystem.

The third subsystem is responsible for determining the operation mode of the bidirectional converter depending on the sign of the difference in entropy of the generation and consumption flows. If the entropy difference is less than or equal to zero, the signal from the second subsystem is fed to the transistors, so that the bidirectional converter operates in the mode of a discharging device and, therefore, discharges the storage device. Accordingly, if the entropy difference is greater than zero, the converter operates in the charging mode and charges the energy storage.

The control unit models are represented by the corresponding blocks:

- Constant is a constant signal generator with a set value of 220V;
- Sum is a summator;
- Integrator is a key component of the PI controller that implements an integral action;
- Saturation is a signal limiting block;
- Sawtooth is a block for sawtooth signal generation;
- Relational Operator is a block for comparing input signals.

The entropy calculation system consists of two parallel MATLAB Function blocks [27] that calculate the Shannon power entropy at the model input and output with a frequency of 6 seconds (corresponding to one hour of real time) using the following equation [28]:

$$H(p) = -\sum_i p_i \log_2 p_i \,, \tag{2}$$

where p_i is the probability of the i-th power value on the source or a consumer side. It is important to note that the entropy is calculated at the end of a certain time interval, in this case being an hour.

The system also uses the Unit Delay [29] and Zero-Order Hold [30] blocks to ensure proper sampling of the input power data before being fed to the input of the MATLAB Function blocks for entropy calculation.

The difference in entropies of the generation and consumption flows is fed to a relay element that generates a control signal (meander type) for the key that switches the energy storage.

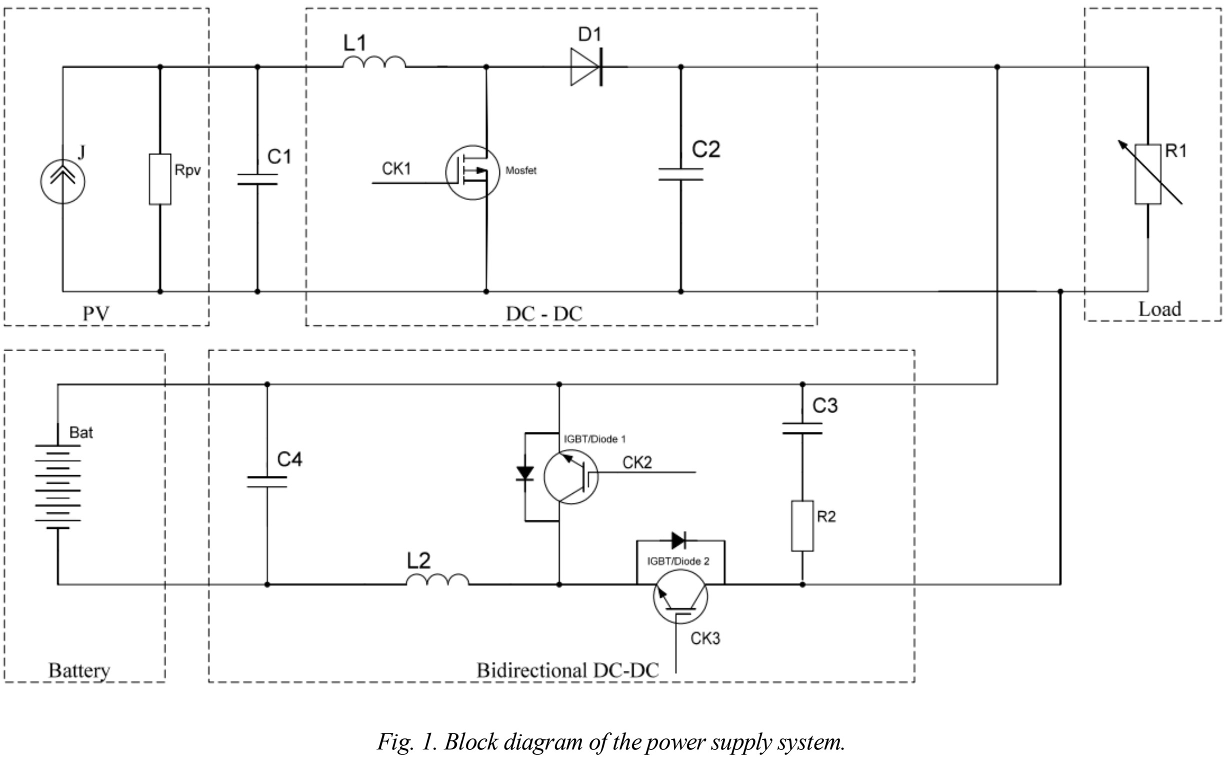


Fig. 1. Block diagram of the power supply system.

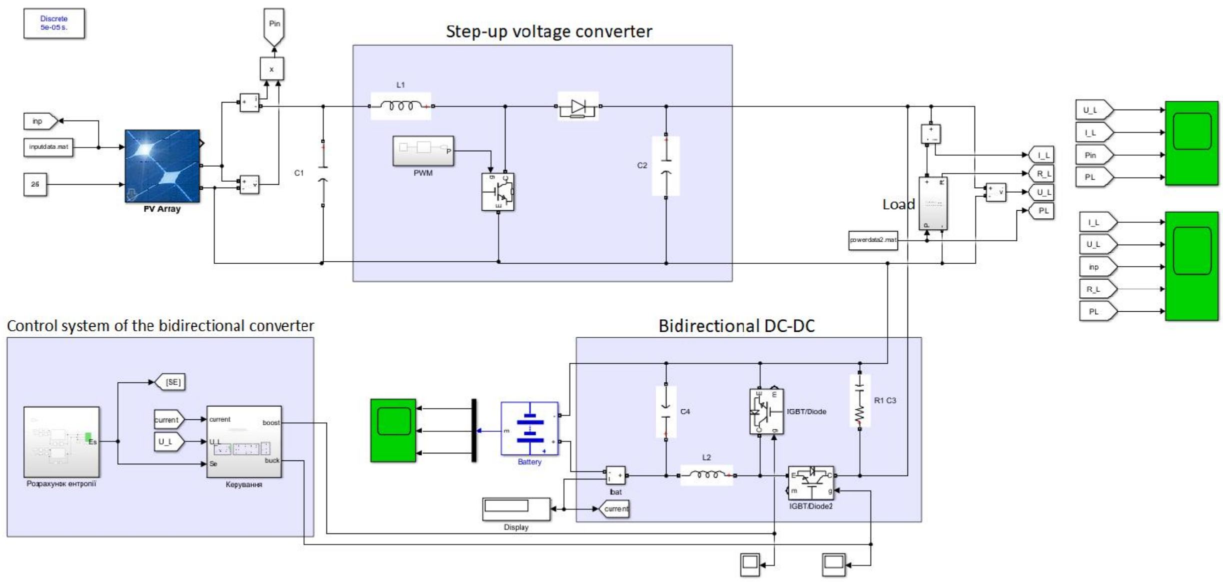
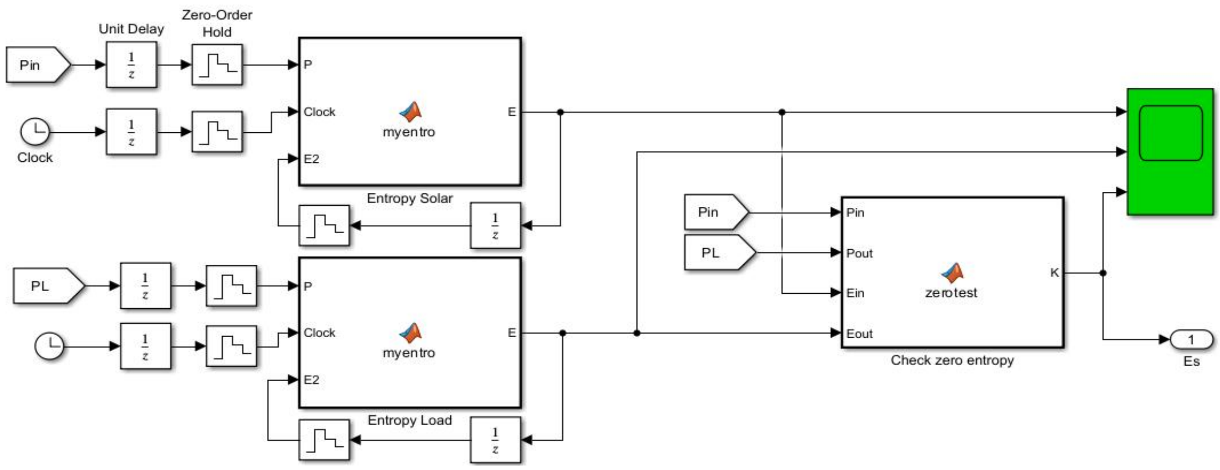
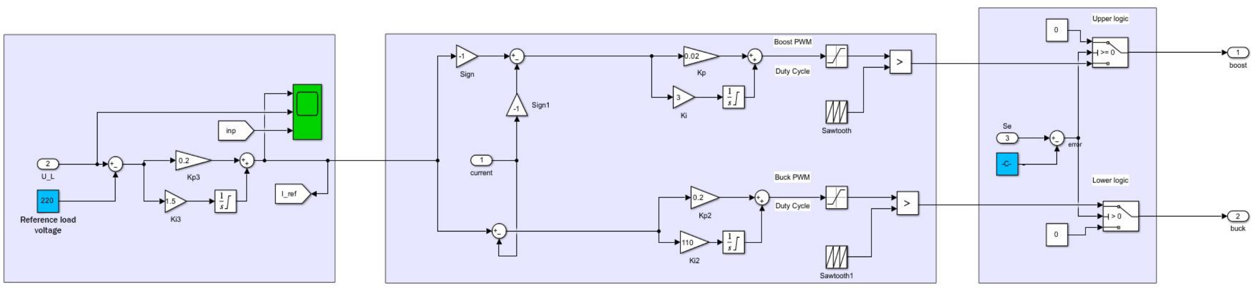


Fig. 2. Block diagram of the model of the power supply system.



a

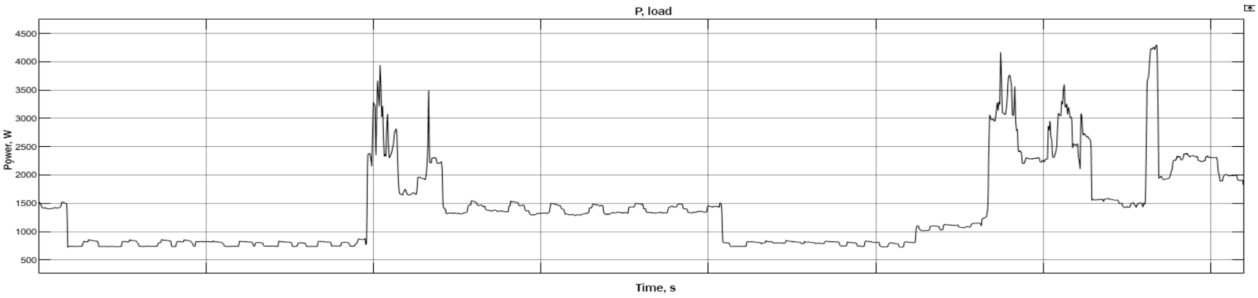


b

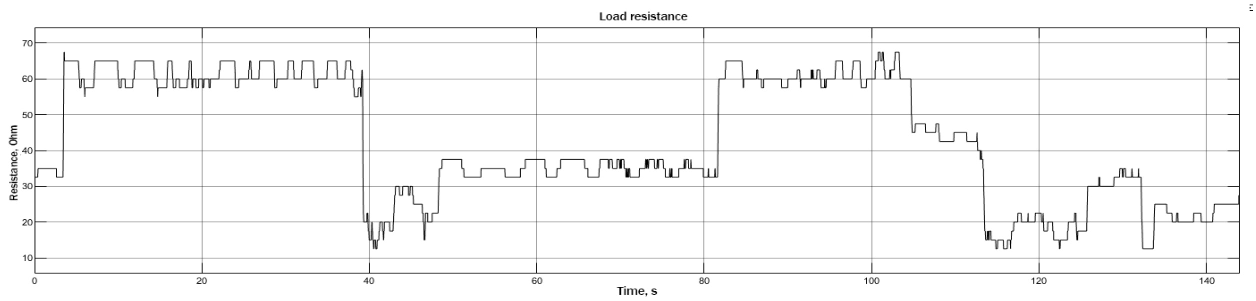
Fig. 3. Block diagrams of subsystem models of the unit for entropy calculation (a) and control unit (b).

5. Simulation results

Modeling of electrical processes in the power supply system was carried out both with control function considering the entropy difference and without it. Fig. 4 presents graphs of changes in power consumption and load resistance generated by the adaptive variable load unit. In addition, after the simulation, the graphs of the change in the output power of the solar battery and the load (Fig. 5, a, b) were obtained, as well as the graph of the change in the battery charge state (Fig. 5, c) during the simulation time, which was set being one day.

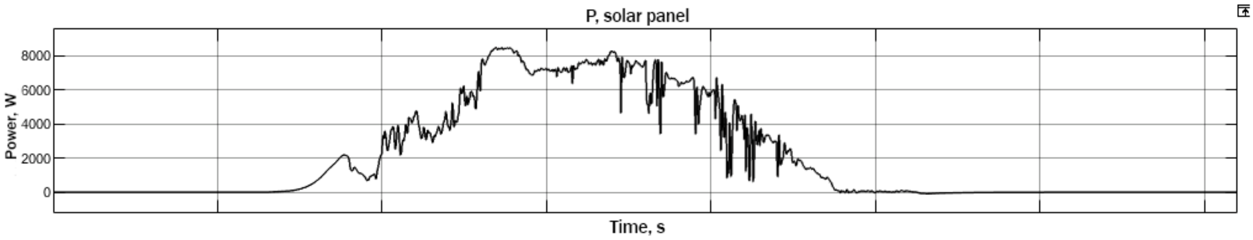


a

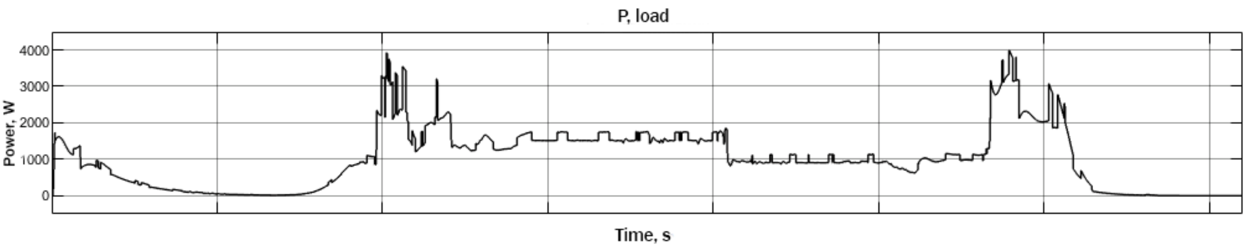


b

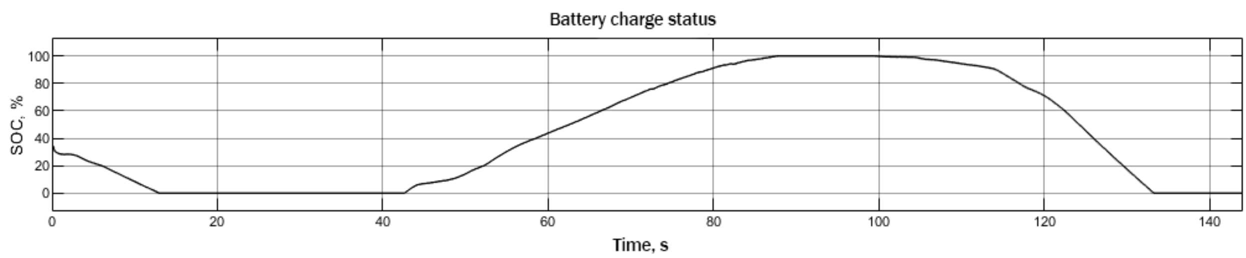
Fig. 4. Graphs of power consumption (a) and load resistance (b).



a



b



c

Fig. 5. Graphs: power output of the solar battery (a), load power (b),
state of charge of the storage device (c).

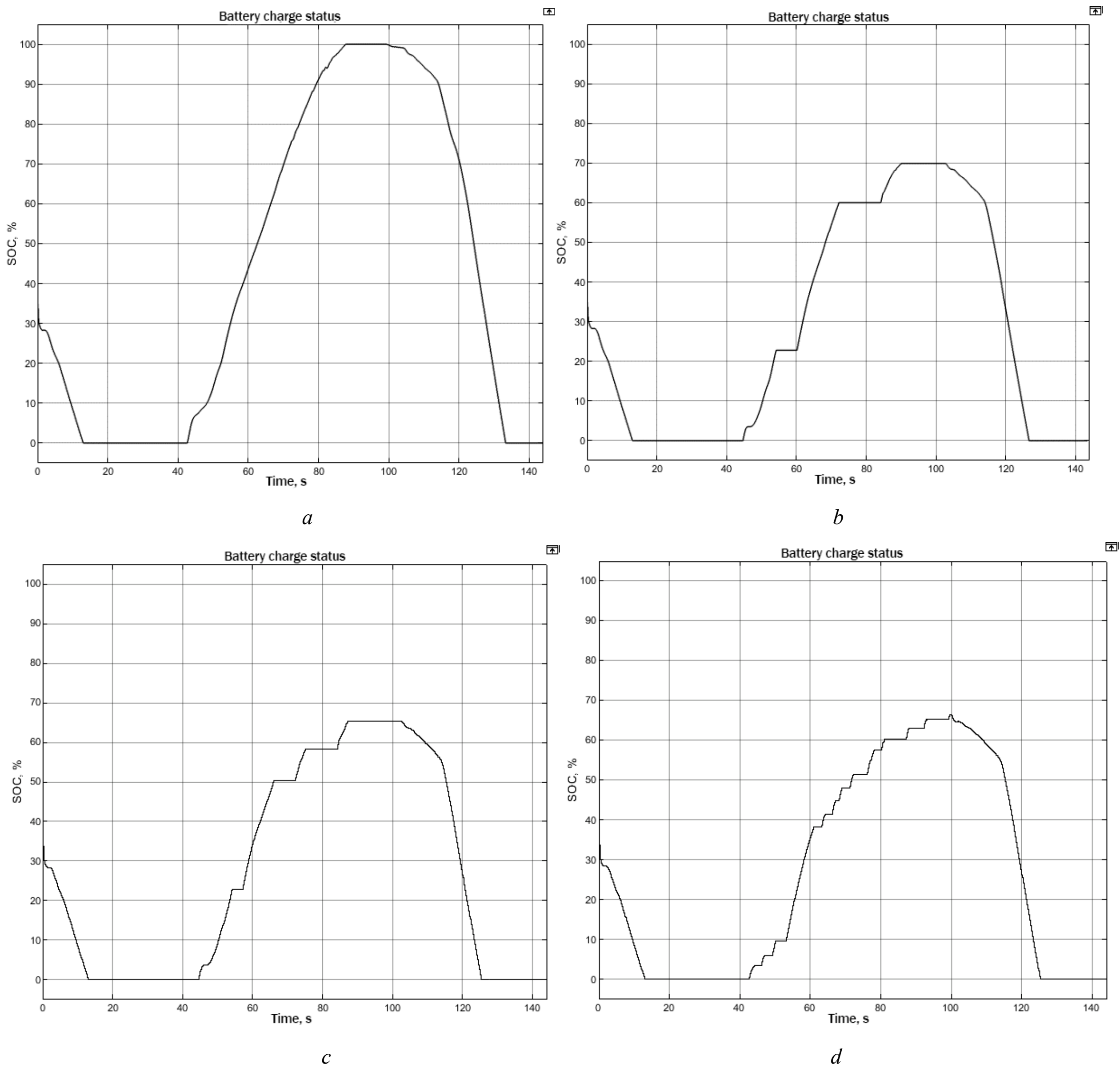


Fig. 6. Graphs of changes in the state of charge of the energy storage: a) control without taking into account the entropy difference; b) control with taking into account the entropy difference at an interval of 60 minutes; c) control with taking into account the entropy difference at an interval of 30 minutes; d) control with taking into account the entropy difference at an interval of 10 minutes.

To evaluate the impact of the accuracy of determining the entropy values on the modeling results, the entropy for different interval durations (60 minutes, 30 minutes and 10 minutes) was calculated (Fig. 6).

Thus, the developed model allows for simulating electromagnetic processes in the power supply system. In order to achieve efficient control of the charging and discharging devices, a control system was developed based on the calculation of the difference in entropy of the generation and consumption flows. This system allows for reducing the duration of time intervals when the energy storage is uncontrollable while being fully charged or fully discharged.

The detailed study and analysis of the modeling results can help develop optimal system control strategies maximizing the efficiency of the available energy resources and ensuring stable and reliable power supply to the load.

6. Conclusion

The model of the power supply system proposed in the article, which takes into account the stochastic nature of energy generation and consumption processes, allows evaluating the ratio of energy generation and consumption and their impact on the charge state of the energy storage. To build the model, it is necessary to obtain data on solar irradiation and electricity consumption with a discreteness of 1 minute, as well as take into account the control algorithm of the bidirectional converter based on calculating the entropy difference of generation and consumption flows. The obtained model can be used to develop optimal control strategies for the power supply system in order to maximize the use of available energy resources and ensure stable power supply to the load.

References

[1] *Matlab and Simulink Basics*, Problem-Based Learning in Communication Systems Using Matlab and Simulink, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2016. https://doi.org/10.1002/9781119060239.ch1

[2] Rostyslav Marchenko and Kateryna Klen, "Prediction of Load Capacity in Microgrid by Multiple Regression Method", *Microsystems, Electronics and Acoustics*, vol. 27, no. 1, p. 236697-1, 2022. DOI: 10.20535/2523-4455.mea.236697. (in Ukrainian)

[3] K. S. .Klen, "First Sample Entropy as a Function of the State of a Distributed Generation System", *"Microsystems, Electronics and Acoustics"*, vol. 26, no. 1, p. 228315-1, 2021. DOI: 10.20535/2523-4455. (in Ukrainian)

[4] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg and B. Lehman, "Step-Up DC–DC Converters: A Comprehensive Review of Voltage-Boosting Techniques, Topologies, and Applications," *IEEE Transactions on Power Electronics*, vol. 32, no. 12, pp. 9143-9178, Dec. 2017. DOI: 10.1109/TPEL.2017.2652318

[5] R. E. Andrienko, K. S. Klen, "Simulation modeling of an autonomous power supply system based on solar panels in real time", "*Microsystems, Electronics and Acoustics*", (2022) 27(3) 268903–1. https://doi.org/10.20535/2523-4455.mea.268903

[6] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal*, vol. 27, no. 3, pp. 379-423, July 1948. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

[7] DOI: 10.1002/j.1538-7305.1948.tb01338.x

[8] S. Bououden, O. Hazil, S. Filali and M. Chadli, "Modelling and model predictive control of a DC-DC Boost converter", in *Proc. 15th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*, Hammamet, Tunisia, pp. 643-648, 2014. https://doi.org/10.1109/sta.2014.7086663

[9] J. -H. Teng, S. -W. Chen, S. -W. Luan and J. -R. Xu, "Bidirectional DC-DC Converter with a Wide-Range Voltage Conversion Ratio", in *Proc. IEEE 4th International Future Energy Electronics Conference (IFEEC)*, Singapore, pp. 1-6, 2019. https://doi.org/10.1109/ifeec47410.2019.9014688

[10] Z. Saadatizadeh, P. C. Heris, Y. Yang and F. Blaabjerg, "High Step-Up/Down Switched-Capacitor Based Bidirectional DC-DC Converter", *IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL*), Aalborg, Denmark, pp. 1-6, 2020. https://doi.org/10.1109/compel49091.2020.9265735

[11] S. Surya, J. Channegowda, S. D. Datar, A. S. Jha and A. Victor, "Accurate Battery Modeling Based on Pulse Charging using MATLAB / Simulink", in *Proc. IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Jaipur, India, pp. 1-3, 2020. https://doi.org/10.1109/pedes49360.2020.9379617

[12] B. Joshi, J. K. Maherchandani and A. A. Chhipa, "Comparison Between Open and Closed Loop Battery Charging Technique for Lithium-ion Battery", in *Proc. 7th International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, pp. 150-155, 2021. https://doi.org/10.1109/icees51510.2021.9383692

[13] B. Yang, Y. Wang, X. Zhou and Y. Ma, "Design of Bidirectional DC-DC Converter Control Based on Arrange the Transition Process", in *Proc. Chinese Control And Decision Conference (CCDC)*, Nanchang, China, pp. 5064-5069, 2019. https://doi.org/10.1109/ccdc.2019.8832650

[14] N. Yadav and D. K. Sambariya, "Mathematical Modelling and Simulation of Photovoltaic Module Using MATLAB/SIMULINK", in *Proc. 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Bengaluru, India, pp. 1-6, 2018. https://doi.org/10.1109/icccnt.2018.8494167

[15] L. W. Yao, J. A. Aziz, P. Y. Kong and N. R. N. Idris, "Modeling of lithium-ion battery using MATLAB/simulink", in *Proc. 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, pp. 1729-1734, 2013. https://doi.org/10.1109/iecon.2013.6699393

[16] D. Athaide, J. Qin and Y. Zou, "MATLAB/Simulink-Based Electromagnetic Transient-Transient Stability Hybrid Simulation for Electric Power Systems with Converter Interfaced Generation", in *Proc. IEEE Texas Power and Energy Conference (TPEC)*, College Station, TX, USA, pp. 1-6, 2019. https://doi.org/10.1109/tpec.2019.8662135

[17] IRENA, "Renewable Energy Capacity Highlights," Int. Renew. Energy Agency, vol. 00, no. April 2022, 2022, *https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_-RE_Capacity_Highlights_2022.pdf*

[18] IRENA, "Renewable Capacity Statistics 2022," Int. Renew. Energy Agency, 2022, *https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_RE_Capacity_Statistics_2022.pdf*

[19] S. P. Europe, "Global Market Outlook For Solar Power 2022-2026," Sol. Power Eur., 2022, *https://api.solarpowereurope.org/uploads/Solar_Power_Europe_Global_Market_Outlook_report_2022_2022_V2_07aa98200a.pdf*

[20] IRENA, "Future of solar photovoltaic," 2019, *https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf*

[21] “ZAKON UKRAYINY Pro al□ternatyvni dzherela enerhiyi[LAW OF UKRAINE On Alternative Energy Sources].”, *https://www.gpee.com.ua/get_document/72*
[22] “International Energy Agency. (2022). Renewables 2022: Analysis and forecast to 2027.” *https://www.iea.org/reports/renewables-2022*
[23] SunPower 305 Solar Panel,” *https://www.pocosolar.com/wp-content/themes/twentyfifteen/pdfs/Sunpower%20Solar%20Panels/sunpower_305wht_spec_sheet.pdf*
[24] “To Workspace.”, *https://www.mathworks.com/help/simulink/slref/toworkspace.html*
[25] “Laboratory for Renewable Energy Systems (LARES) of University of Zagreb, Faculty of Electrical Engineering and Computing.” *https://www.lares.fer.hr/*
[26] “Household Electric Power Consumption.”, *https://www.kaggle.com/datasets/uciml/electric-power-consumption-data-set?resource=download*
[27] “Variable Resistor in DC.”, *https://www.mathworks.com/matlabcentral/fileexchange/61022-variable-resistor-in-dc*
[28] “PID Controller.”, *https://www.mathworks.com/help/simulink/slref/pidcontroller.html*
[29] “MATLAB Function.”, *https://www.mathworks.com/help/simulink/slref/matlabfunction.html*
[30] “Unit Delay.”, *https://www.mathworks.com/help/simulink/slref/unitdelay.html*
[31] “Zero-Order Hold.”, *https://www.mathworks.com/help/simulink/slref/zeroorderhold.html*

ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ СИСТЕМИ ЕЛЕКТРОЖИВЛЕННЯ З ВРАХУВАННЯМ СТОХАСТИЧНОГО ХАРАКТЕРУ ПРОЦЕСІВ ГЕНЕРАЦІЇ Т А СПОЖИВАННЯ ЕНЕРГІЇ

Катерина Клен, Віталій Навроцький, Валерій Жуйков

У статті представлено розрахунок параметрів та імітаційне моделювання системи електроживлення на основі сонячних панелей з врахуванням стохастичних параметрів процесів генерації та споживання енергії. За допомогою моделювання в MATLAB® Simulink було оцінено продуктивність системи електроживлення при зміні величини сонячної інсоляції та потужності навантаження. Описано спосіб керування двонаправленим перетворювачем на основі розрахунку різниці ентропії Шеннона потоків генерації та споживання енергії. Цей метод дозволяє підвищити ефективність використання енергії в системі за рахунок зменшення різниці між значеннями ентропії на вході та виході системи. Також це дозволяє скоротити тривалість часових інтервалів, коли накопичувач енергії в системі є неконтрольованим: повністю зарядженим або повністю розрядженим. Моделювання електричних процесів в системі електроживлення проводилось як з реалізацією керування на основі розрахунку різниці ентропій, так і без нього. Для оцінки впливу точності розрахунку значень ентропії на результати моделювання було проведено розрахунок ентропії для різної тривалості інтервалів. Проведено аналіз результатів моделювання системи електроживлення з використанням даних інсоляції та потужності навантаження з дискретністю в 1 хвилину.

Kateryna Klen (Born 17.12.1989) – PhD, assosiate professor of Department of Electronic Devices and Systems, “Igor Sikorsky Kyiv Polytechnic Institute” National Technical University of Ukraine, Kyiv, Ukraine.

Research interests: analysis and calculation of the electronic circuits using the method of structural numbers; converters in Smart Grid; maximum power point tracking for renewable energy sources; approximation of the primary energy flow change function.

Vitalii Navrotskyi (Born 04.10.2000) – bachelor of Department of Electronic Devices and Systems, “Igor Sikorsky Kyiv Polytechnic Institute” National Technical University of Ukraine, Kyiv, Ukraine.

Research interests: control systems of alternative energy sources.

Valery Zhuikov (Born 18.11.1945) – professor, D.Sc., Dean of the Faculty of Electronics, “Igor Sikorsky Kyiv Polytechnic Institute” National Technical University of Ukraine, Kyiv, Ukraine.

Research interests: calculation theory of transient and steady-state processes in power electronic devices; analysis, synthesis and optimization of electronic systems; deterministic chaotic processes in converters; intelligent control of power consumption.

Received: 28.10.2023, Accepted: 25.11.2023