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RENEWABLE ENERGY SOURCES

Experimental Test Bed of a Hybrid Power Plant with a Common DC Bus and the Use of Unified Controllers for Various Sources, Loads, and Storages

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Abstract—At the Joint Institute for High Temperature, Russian Academy of Sciences, a power plant scheme has been developed and implemented in the form of an operating test bed, which includes several energy sources (solar battery, electrochemical generator), a storing device (accumulator battery), a base load, and an additional consumer (an electrolyzer, a heat/cold generator, or redox-flow battery). All devices are connected to a common DC bus through individual matching converters that have the same hardware and software implementation. The created test bed with a data acquisition and processing system can be used to study various schemes for control of hybrid power plants, including not only renewable energy sources, but also selected groups of consumers for excessive production of hydrogen, heat, cold, and purified water. In the course of field tests, the possibilities of controlling energy flows due to the DC bus voltage control are demonstrated: the introduction of a guaranteeing source at night and the operation into an electrolyzer simulator during peak solar generation.

Keywords: extreme regulator, hybrid storage, hydrogen energy, energy storage, energy distribution
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INTRODUCTION

Within the sufficiently developed foreign network of photovoltaics, operators of energy networks pose the task of reducing the energy exchange with the network at moments of peak generation in order to decrease fluctuations in regulation powers. The solution to this problem is seen through so-called self-consumption, when a household automatically connects an additional consumer for the utilization of this energy, e.g., water heating, which further allows the consumption of gas or electricity for these purposes to be reduced [1]. It is shown that this solution is more justified today than the use of electrochemical storages [2]. For off-grid systems operating under conditions of the Russian Far East and other similar climatic zones, the problem is also seasonal in nature: a significant drop in the solar radiation level in winter is accompanied by a exponential growth of the consumer's electrical load, which is often based on pumps for heating systems in remote villages [3]. In summer, the dependence is of reverse nature: a significant increase in potential output from a solar battery with a multiple drop in load, which makes one think about seasonal energy storage [4]. First of all, this involves redox-flow batteries [5] and systems generating hydrogen [6], which can then be used to produce thermal or electrical energy [7]. From the viewpoint of the power plant control system, both tasks mean that the system itself must at some point recognize the presence of a potential for excessive energy production and utilize it for additional consumer supply. In this case, the reduction of this excess should lead to restrictions to the supply of an additional consumer up to its complete shutdown [8] and the introduction of a guaranteeing source when this excess is completely exhausted [9]. There is also a fairly large number of inverters and controllers of charge on the market that could act as the control and energy conversion systems in various hybrid plants [10]. However, most of them (if solar photoenergy is considered as an example) are designed for systems such as "solar battery–grid" [11], "solar battery–storage–load" [12], or "solar battery–storage–diesel–generator–load" [13]. Working with an indicated group of loads or an additional storage requires the addition of these systems with the supplemental equipment, e.g., with the WattRouter system [14].The products of SMA Solar Technologies [15] are

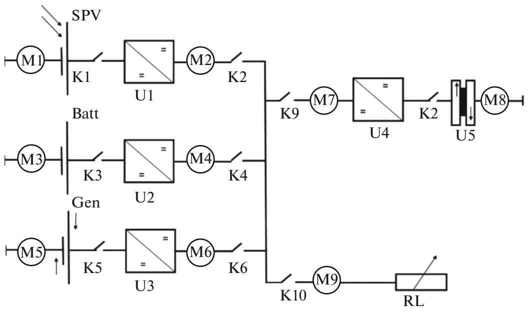


Fig. 1. Block diagram of a hybrid power plant on a common DC bus. SPV is the solar battery, U1–U4 are extreme regulators SPZ 25-40, U5 is the electrolyzer (or simulator), Batt is the storage battery, Gen is the electrochemical generator (or simulator), RL is the base (target) load, K1–K10 are the circuit breakers, M1–M9 are the connection points for the current and voltage measureme equipment.

the most universal in terms of connecting almost any loads and consumers to a common AC bus through a family of inverters and chargers; however, here the problems are associated with the high cost of these products and additional energy losses during the conversion of DC to AC. The approach adopted for electric vehicles with a common high-voltage DC bus [16] and one inverter for AC consumers at the output (if necessary) is more promising.

The paper considers the operating test bed of a hybrid system with a common low-voltage DC bus (at the stage of engineering tests), which uses controllers identical in hardware and software to connect various devices to the bus: sources, consumers, and energy storages. This scheme allows the system to be controlled through a single parameter: a voltage on the common bus. The specific features of the connected devices are taken into account at the stage of programming the operating modes of the controllers by setting the actual currents and voltages during the power beginning or supply. The main tasks to be solved are: checking the operation of controllers as part of the hybrid power plant and adjusting the values of currents and voltages to achieve a certain order of connection and disconnection of sources and consumers.

MATERIALS AND METHODS

At the Joint Institute for High Temperatures, Russian Academy of Sciences, a power plant scheme has been developed, which includes several energy sources (solar battery, electrochemical generator), a storage (accumulator battery), a base load, and an additional consumer (an electrolyzer or redox-flow battery). All devices are connected to a common DC bus (CDCB) through individual matching converters (Fig. 1).

Figure 1 shows a photovoltaic module (primary energy source), a battery (Batt) designed to cover short-term dips in the energy production and consumption, an electrolyzer simulator (U5) that absorbs excess production of a photovoltaic module, and an electrochemical generator simulator (Gen) that is a guaranteeing source of power supply of a consumer, multi-stage resistive load (RL). The control of sources and the electrolyzer simulator is performed by SPZ 25-40 regulators (U1–U4), the measurement of currents and voltages is carried out by analog-to-digital converters M1–M9. Circuit breakers K1–K10 are designed to protect circuits from short circuit and overload, as well as for the convenience of operational switching.

The operation of the sources is controlled by sustaining a level of a constant operating voltage of the bus due to the energy output or extraction by the controllers. In this case, different voltage values are set for different sources. For the implementation of a scheme with seasonal energy storage in a test-bed version, a hydrogen cycle is considered due to the higher availability of components and a wider range of operating temperatures for balloon storage of hydrogen, compared to a redox battery [17].

The optimal control device, SPZ 25-40, developed jointly with the LLC Yarostanmash, acts as a controller. The device has a conditional input (to which a primary or secondary power source can be connected) and an output (for connecting a consumer or a DC bus). The device basis is a bidirectional DC-to-DC converter, which works both for increasing and decreasing the voltage and is built on the basis of the STM32 microcontroller [11]. Therefore, the input and output are conditional: in the mode of charging the battery or powering the consumer from the CDCB, in fact, they change places. There are three operating modes available for the device:

— Extreme power regulator. In this mode, the maximum power is taken (with given current and voltage limits in the bus) from the source in the CDCB.

— Uninterruptable power source. In this mode, the SPZ 25-40 is connected to the battery and to the CDCB that connects the primary source and the consumer. If the voltage on the CDCB is higher than the specified value, then a two-stage battery charging takes place (with a direct current up to a given voltage, then this voltage is maintained until the current drops within certain limits). If the battery voltage is high enough and the battery is determined as a charged one, then the controller only traces the voltage on the CDCB. When the voltage drops below the specified value, the battery discharge occurs to supply the consumer until the voltage on the CDCB normalizes.

— Voltage stabilizer. When the specified value of the voltage on the CDCB is exceeded, energy is taken from the CDCB (an additional storage device or energy consumer can be connected to the second output of the controller), if the voltage is too low, energy is output to the bus (in this case, a guaranteeing power supply must be connected to the second input).

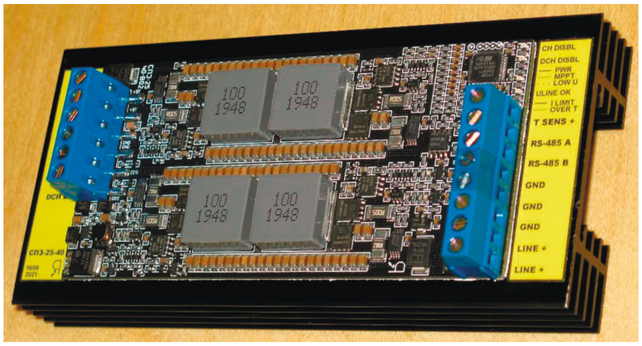


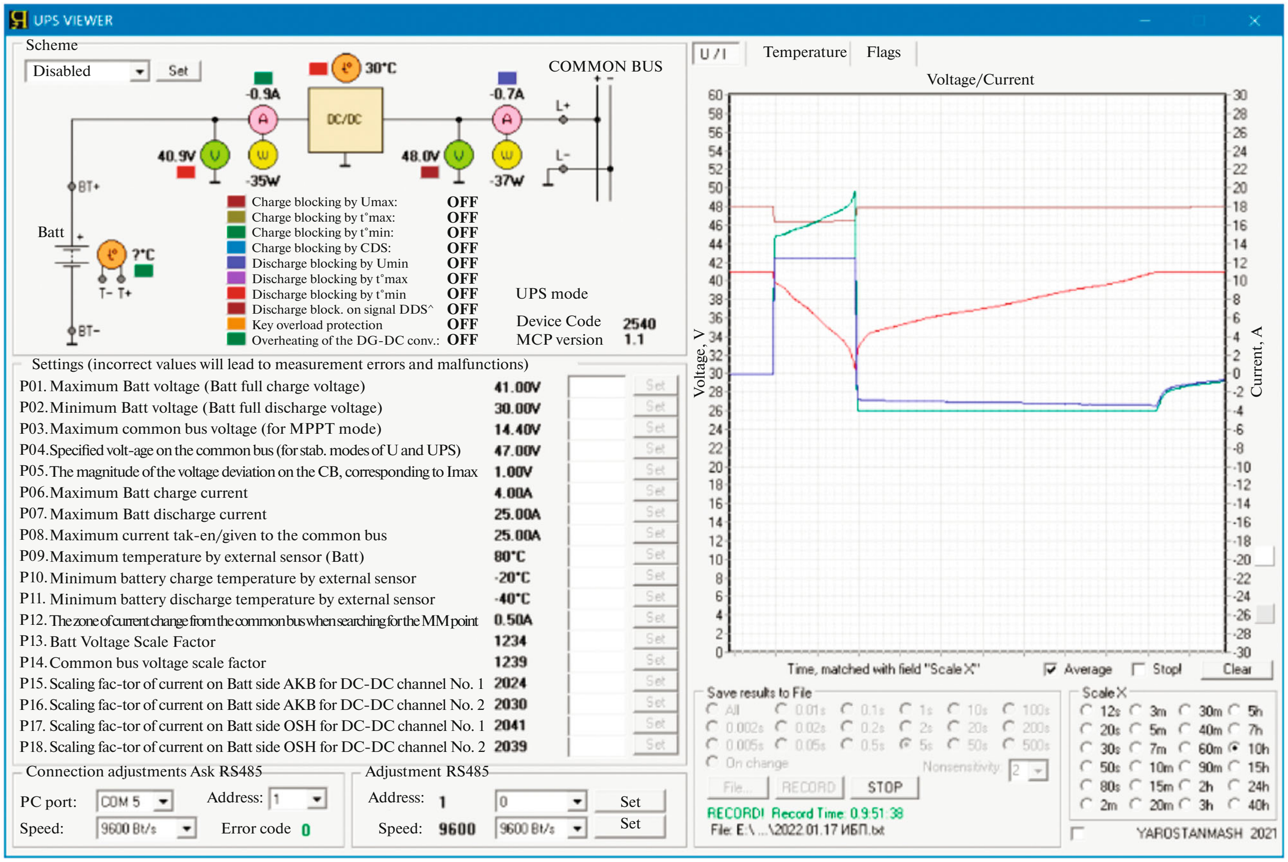
Fig. 2. Appearance of the extreme SPZ 25-40 regulator.

In all modes, maximum current limitations through the controller are available (below 25 A, which is a hardware restriction) and the ability to reach the maximum current only at certain values of voltage deviation from the set value. The appearance of SPZ 25-40 is shown in Fig. 2.

The input of parameter values and modes is carried out from a personal computer via the RS485 interface and special software. The interface of the software installed on the computer in the form of an EXE file is shown in Fig. 3

Figure 3 shows the instantaneous values of currents and voltages of the controller input/output, as well as the available parameter values for programming the device, some of which are displayed on its mnemonic diagram.

To test the practical application of hybrid circuits, an experimental facility was created, which includes a CDCB with four extreme SPZ 25-40 regulators. A TopraySolar photovoltaic module [12] is connected to the conditional input of one of them, two lithium-nanotitanate batteries (18 A·h, 16 V) manufactured by Phoenix Ultracapacitors are connected to the other input. A laboratory power supply (5 A, 30 V) as a simulator of an electrochemical generator based on fuel cells was used at the stage of testing control algorithms, and as a simulator of an electrolyzer, an active load was used, the power resistors of which (of AN100 type) were selected from the condition of power dissipation of 150 W at a voltage of 14 V. The base load includes 15 blocks of AN100 resistors [13] connected in parallel, switched by automatic breakers. This makes it possible to put into operation different load blocks depending on the time of day and to simulate the work of various consumers. The total load power is 1.5 kW at a voltage of 24 V on the CDCB.



Scheme: Disabled

🟥	Charge blocking by Umax:	OFF
🟫	Charge blocking by t°max:	OFF
🟩	Charge blocking by t°min:	OFF
🟦	Charge blocking by CDS:	OFF
🟦	Discharge blocking by Umin	OFF
🟪	Discharge blocking by t°max	OFF
🟥	Discharge blocking by t°min	OFF
🟥	Discharge block. on signal DDS^	OFF
🟧	Key overload protection	OFF
🟩	Overheating of the DG-DC conv.:	OFF

UPS mode

Device Code 2540

MCP version 1.1

Settings (incorrect values will lead to measurement errors and malfunctions)

P01. Maximum Batt voltage (Batt full charge voltage)	41.00V
P02. Minimum Batt voltage (Batt full discharge voltage)	30.00V
P03. Maximum common bus voltage (for MPPT mode)	14.40V
P04. Specified volt-age on the common bus (for stab. modes of U and UPS)	47.00V
P05. The magnitude of the voltage deviation on the CB, corresponding to Imax	1.00V
P06. Maximum Batt charge current	4.00A
P07. Maximum Batt discharge current	25.00A
P08. Maximum current tak-en/given to the common bus	25.00A
P09. Maximum temperature by external sensor (Batt)	80°C
P10. Minimum battery charge temperature by external sensor	-20°C
P11. Minimum battery discharge temperature by external sensor	-40°C
P12. The zone of current change from the common bus when searching for the MM point	0.50A
P13. Batt Voltage Scale Factor	1234
P14. Common bus voltage scale factor	1239
P15. Scaling fac-tor of current on Batt side AKB for DC-DC channel No. 1	2024
P16. Scaling fac-tor of current on Batt side AKB for DC-DC channel No. 2	2030
P17. Scaling fac-tor of current on Batt side OSH for DC-DC channel No. 1	2041
P18. Scaling fac-tor of current on Batt side OSH for DC-DC channel No. 2	2039

Connection adjustments Ask RS485

PC port: COM 5 Address: 1

Speed: 9600 Bt/s Error code 0

Adjustment RS485

Address: 1 0

Speed: 9600 9600 Bt/s

☑ Average ☐ Stop!

Save results to File: ● 5s

Nonsensitivity: 2

RECORD! Record Time: 0:9:51:38

File: E:\ ...\2022.01.17 ИБП.txt

Scale X: ● 10h

☐ YAROSTANMASH 2021

Fig. 3. Screenshot of the control software interface of the SPZ 25-40 regulator.

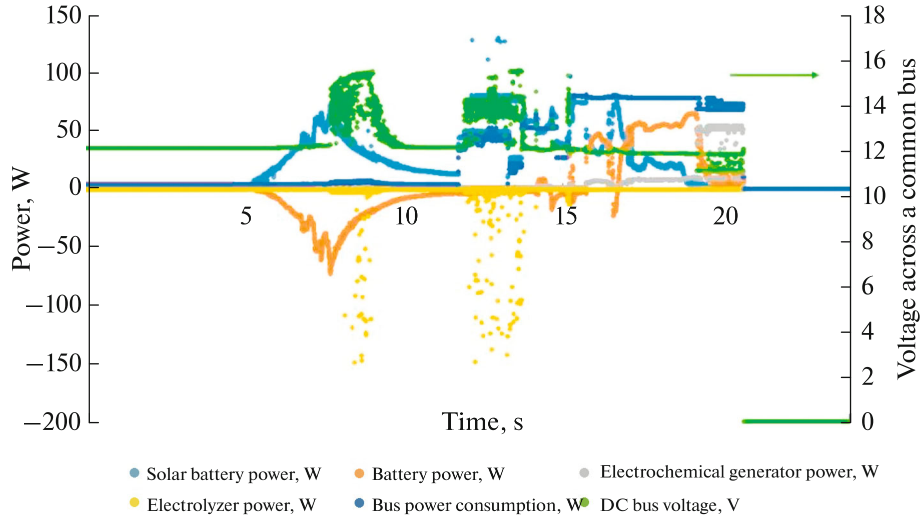


Fig. 4. Test results (distribution of power flows) with a load schedule close to a typical one for a centralized network.

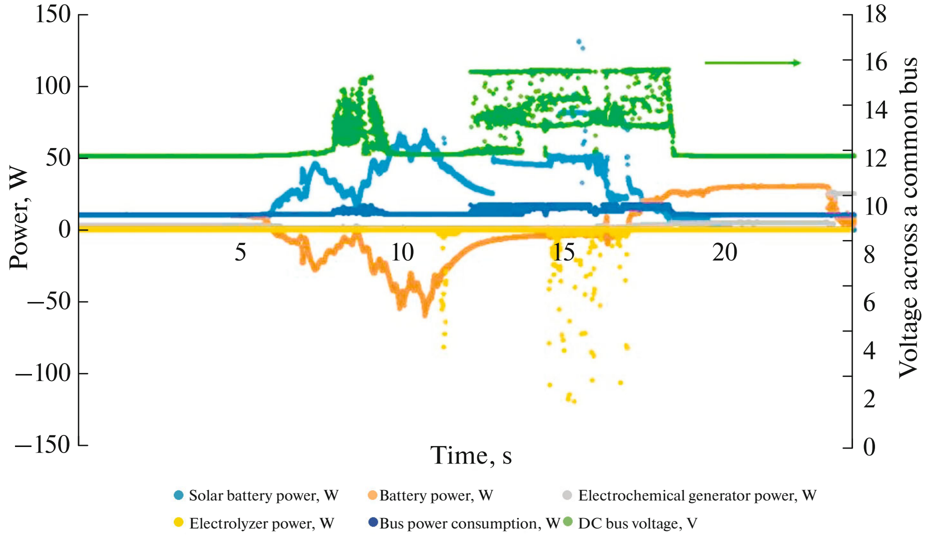


Fig. 5. Test results (distribution of power flows in Fig. 1) at a constant load with an electrochemical generator as a voltage stabilizer.

The measurement system is based on devices of the OWEN company. Measurements of currents and voltages at M1–M9 are carried out by an OWEN MV 110.224-2A analog-to-digital converters (ADCs) [14] using current shunts of the SHIP type and voltage dividers based on CF-25 resistors [15]. To measure voltage, an input with limits of 0–1 V is used, for measuring current, an input with limits from –50 to 50 mV is used. After assembling the circuit, the measuring channels were calibrated to obtain calibration voltage coefficients by connecting a laboratory power source and a rheostat to each line in series. Data collection from the ADC is carried out by the OWEN MSD-200 archiver [16], which sequentially interrogates all ADCs using the Modbus ASCII protocol (RS 485 interface) with data recording in .csv format on an SD card. Data processing is carried out in the Excel program.

The general ideology of system operation is similar to the traditional one for similar hybrid circuits [17, 18] and is that the photovoltaic module is the primary source of energy, the battery is the main storage device that compensates for load and output unevenness, and the electrolyzer is an additional energy consumer that turns on when the battery is fully charged and the base load is covered, while excess production is still present. The electrochemical generator, due to its relatively short resource [19, 20] and high cost, serves as a guar-

Table 1. Operating modes of SPZ 25-40 regulators

Source/Consumer of energy behind the regulator	Operating mode	Maintained voltage on CDCB, V
Photovoltaic module	Extreme power controller	16
Battery	Voltage stabilizer	12.4
Electrochemical generator	Uninterruptible power supply	12.4
Electrolyzer	Voltage stabilizer	13.5

anteeing power source and turns on only when the battery is discharged.

RESULTS AND DISCUSSION

Figure 4 shows a schedule of daily operation of the facility with a variable load, simulating a typical schedule of electricity consumption in a centralized network.

In the morning hours, with no load, all the energy generated by the photovoltaic module was directed to charge the battery. Then, as the battery voltage grew, the electrolyzer simulator turned on. After the load appeared, it was powered mainly by a photovoltaic module, however, its further growth, together with a decrease in the solar radiation level in the afternoon, led to bringing, at first, the battery into operation and then a guaranteeing power supply. Figure 5 shows an example of daily operation with a load value close to constant.

In this case, the storage battery was also charged at first, while the excess energy was transferred to the electrolyzer simulator. In the evening, the consumer was powered mainly by the battery with little support from the electrochemical generator simulator, which was completely put into operation after the battery charge was exhausted. The transfer of the regulator connected to the electrochemical generator into the mode of an uninterruptible power supply made it possible to significantly reduce the load on the electrochemical generator. The final version of the voltage values at the CDCB, implemented by various regulators, are presented in Table 1.

Thus, a control scheme for a group of the energy sources and consumers as part of a hybrid power plant with a common DC bus has been implemented. The possibility of controlling energy flows in the plant due to a change of voltage levels sustained by regulators connected to various devices (sources and consumers) is shown. The operation modes of the sources are also important. It should be noted that instead of an electrolyzer, in this case, an air conditioner, a thermal electric heater, or a water purification system can be connected to the CDCB to utilize the excess energy received from the solar battery. In this case, it is important to note that any number of other consumers/sources/storages of energy can be connected to the CDCB through similar devices.

CONCLUSIONS

An extreme power regulator with the functions of a SPZ 25-40 regulator has been developed and manufactured, which allows an operation with a wide range of DC sources and consumers (0–25 A, 12–40 V). To test the regulator as part of a hybrid power plant that implements the use of solar energy to power consumers with the possibility of using several energy storage devices, an operating model of this plant with five channels (solar battery, electrochemical battery, electrolyzer, electrochemical generator, and base load), equipped with means for measuring current and voltage before and after the regulators was created. The possibility of regulating the power flows in this system by changing the values of the output voltage of the regulators on a common DC bus, connecting the sources and the load, is shown. Using a real photovoltaic module, a battery, as well as simulators of an electrolyser and an electrochemical generator, the modes were tested and the voltage values at the output of the regulators were selected to implement a physical model of the hydrogen cycle of electricity storage. Due to the developed automated measurement system and multistage electrical load, this test bed can be used to test control algorithms for a wide range of hybrid power plant schemes with a common DC.

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REFERENCES

1. Torres-Rivas, A., Palumbo, M., Jiménez, L., and Boer, D., Self-consumption possibilities by rooftop PV and building retrofit requirements for a regional building stock: The case of Catalonia, *Sol. Energy,* 2022, vol. 238, pp. 150–161.
2. Lara, E.G., Techno-economic model of nonincentivized self consumption with residential PV systems in the context of Dominican Republic: A case study, *Energy Sustainable Dev.,* 2022, vol. 68, pp. 490–500.
3. Ivanin, O.A. and Direktor, L.B., The use of artificial neural networks for forecasting the electric demand of stand-alone consumers, *Therm. Eng.,* 2018, vol. 65, no. 5, pp. 258–265.

4. Popel, O.S. and Tarasenko, A.B., Hybrid electric energy storages: Their specific features and application (review), *Therm. Eng.,* 2018, vol. 65, no. 5, pp. 266–281.
5. Kim, J. and Park, H., Recent advances in porous electrodes for vanadium redox flow batteries in grid-scale energy storage systems: A mass transfer perspective, *J. Power Sources,* 2022, vol. 545, p. 231904.
6. Felipe Gallardo, Jose García, Andrea Monforti Ferrario, Gabriele Comodi, and Justin N.W. Chiu, Assessing sizing optimality of OFF-GRID AC-linked solar PV-PEM systems for hydrogen production, *Int. J. Hydrogen Energy,* 2022, vol. 47, pp. 27303–27325.
7. Nefedkin, S.I., Barsukov, A.O., Mozgova, M.I., Shichkov, M.S., and Klimova, M.A., Autonomous energy supply based on the wind-energy complex and hydrogen energy storage, *Int. Sci. J. Altern. Energy Ecology,* 2019, vols. 16–18, pp. 12–26.
8. Khamitov, R.N., Kovalev, V.Z., Archipova, O.V., and Esin, S.S., Model of a regionally isolated electro-technical complex with regard to electric load schedules of consumers, *Int. J. Appl. Fundam. Res.,* 2018, vol. 12, pp. 200–204.
9. Pietari Puranen, Antti Kosonen, and Jero Ahola, Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates, *Sol. Energy,* 2021, vol. 213, pp. 246–259.
10. Voltronic Power On-Grid with Energy-Storage Inverter InfiniSolar WP 10KW-15KW.
11. Harb, S., Kedia, M., Zhang, H., and Balog, R.S., Microinverter and string inverter grid-connected photovoltaic system—A comprehensive study, in *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC),* 2013, pp. 2885–2890.
12. Voltronic Power Solar Charge Controller SCC-MPPT. https://voltronicpower.com/en-US/Product/Detail/SCC-MPPT.
13. SMA Sunny Island 5048 Installation and Instruction. https://shop.gwl.eu/docs/pdf/GWL/GWL-SMA-Island-5048-Connection.pdf.
14. Solar Controls S.R.O.—WATTrouters. https://solarcontrols.cz/en/wattrouter.html.
15. Sunny Tripower X. SMA Solar. https://www.sma.de/en/products/solarinverters/sunny-tripower-x.
16. Ji-Yeon Kim, Bom-Seok Lee, Dae-Hun Kwon, Dae-Woo Lee, and Kim Jae-Kuk, Low voltage charging technique for electric vehicles with 800 V battery, *IEEE Transactions on Industrial Electronics,* 2021, vol. 99. https://doi.org/10.1109/TIE.2021.3109526
17. Dassisti, M., Mastrorilli, P., Rizzuti, A., Cozzolino, G., Chimienti, M., Olabi, A.-G., Matera, F., Carbone, A., and Ramadan, M., Vanadium: A transition metal for sustainable energy storing in redox flow batteries, *Encyclopedia of Smart Materials,* 2022, vol. 2, pp. 208–229.
18. STM32 Arm Cortex MCUs - 32-bit Microcontrollers - STMicroelectronics. https://www.st.com/en/microcontrollers-microprocessors/stm32-32-bit-arm-cortex-mcus.html.
19. Topray Solar. https://topraysolar.com/en/Gridconnected/info.aspx?itemid=656.
20. Chipdip. Power resistor AH 100 0.22 Ohm J. https://www.chipdip.ru/product/ah-100-100w-0.22-om-5.
21. Owen. Equipment for Automation. re_oven_mv110-224.2a_2-ru-89611-1.2.pdf (owen.ua).
22. Chipdip. Output resistors EK-R24/3. https://www.chipdip.ru/product/ek-r24-3.
23. Owen. Data acquisition module MSD-200. https://owen.ru/product/msd200.
24. Babatunde, O.M., Munda, J.L., and Hamam, Y., Hybridized off-grid fuel cell/wind/solar PV/battery for energy generation in a small household: A multi-criteria perspective, *Int. J. Hydrogen Energy,* 2022, vol. 47, pp. 6437–6452.
25. Tsai-Chi Kuo, Trang Thi Pham, Duong Minh Bui, Phuc Duy Le, Tan Luong Van, and Po-Tsang Huang, Reliability evaluation of an aggregate power conversion unit in the off-grid PV-battery-based DC microgrid from local energy communities under dynamic and transient operation, *Energy Rep.,* 2022, vol. 8, pp. 5688–5726.
26. Luca, R., Whiteley, M., Neville, T., Shearing, P.R., and Brett, D.J.L., Comparative study of energy management systems for a hybrid fuel cell electric vehicle—A novel mutative fuzzy logic controller to prolong fuel cell lifetime, *Int. J. Hydrogen Energy,* 2022, vol. 47, pp. 24042–24058.
27. Ziliang Gao, Fengfeng Liu, Jinzhan Su, Liejin Guo, and Hongtan Liu, Experimental investigation of reverse voltage phenomenon during galvanostatic start-up of a proton exchange membrane fuel cell, *Energy Convers. Manage.,* 2022, vol. 258, p. 115386.

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