Optimal solutions for an automatic control system for medium capacity power supply facilities using renewable energy sources

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Abstract

Introduction: extensive logistics costs (including long distance transportation and high fuel prices) and a high cost of electric energy, generated by diesel power plants, are the main problem of power supply to consumers by off-grid power systems. The author unlocks the potential of hybrid power systems using renewable energy sources and saving expensive fuel. The author offers the analysis of automatic control systems capable of improving the efficiency of subordinate power plant elements.

Methods: the author provides a classification of wind-diesel power plants and describes their performance pro rata to the share of wind energy consumption. The author has also compiled a set of specifications applicable to the technological solutions of wind-driven power plants. He also formulates the principles underlying an intelligent automatic control system for off-grid power supply facilities. This system served as the basis for a software and hardware module designed and developed for an intelligent power conversion/control/distribution system. The author provides diagrams of (1) electrical circuits of a software and hardware module for an intelligent power conversion/control/distribution system, and (2) the operation of an off-grid power supply package using renewable energy sources and controlled by the power conversion/control/distribution system. The author analyzes the primary and secondary sources of power in an off-grid power supply facility and describes principles of their operation within a software and hardware module.

Results and discussions: the author offers a methodology of intelligent control over off-grid power supply facilities within the framework of the project for development of a wind-diesel power plant in the village of Amderma. The author describes the results of incorporation of a wind-diesel power plant into the power supply facility operating in the permafrost environment of the Arctic region.

Conclusion: presently, Russia has pre-conditions in place capable of boosting the development of power supply technologies using hybrid facilities comprising renewable energy sources. The implementation of such off-grid power supply facilities, controlled by newly designed software and hardware modules designated for an intelligent power conversion/control/distribution system optimizes electric power generation and consumption modes and substantially reduces fuel consumption by diesel power plants.

Keywords: hybrid power plant, wind energy, intelligent control, wind-diesel power plant, high extent of fuel substitution, software and hardware suite, microgrid, Arctic region, renewable energy sources, automatic control systems, cost effectiveness, dynamic control, off-grid power supply, wind-driven power plant

For citation: Elistratov V.V. Optimal’nye resheniya sistemy avtomaticheskogo upravleniya energokompleksov sredney moshchnosti na osnove vozobnovlyaemykh istochnikov energii [Optimal solutions for an automatic control system for medium capacity power supply facilities using renewable energy sources]. *Silovoe i energeticheskoe oborudovanie. Avtonomnye sistemy* [Power and Autonomous Equipment]. 2019. Vol. 2. Issue 2. Pp. 69–85. DOI: 10.32464/2618-8716-2019-2-2-69-85 (In Russian)

INTRODUCTION

Electric power generation by off-grid power supply facilities in northern regions, occupying 60 % of Russia’s territory, is predominantly performed by diesel power plants, whose number, according to the Russian Energy Agency, reaches approximately 900 items, generating about 3 billion kWh a year. The main problems of power supply to off-grid power consumers consists in extensive logistics costs, including long-distance transportation of diesel fuel designated for diesel power plants, low density of the transport infrastructure and a high cost of fuel.

Rising diesel fuel prices boost the rates for the electric power, generated by diesel power plants, which may vary within the range of 15–150 RR/kWh.

The efficient use of renewable energy resources as part of power supply systems, composed of fossil fuel and renewable energy elements, depends on the share of energy from renewable sources that substitutes the energy generated by the combustion of fossil fuel, thus, saving expensive fuel. The author analyzes (1) the control systems, applied to a hybrid power supply facility comprising a modular renewable energy source, and (2) the development of wind-diesel power plants, comprising renewable energy sources, given that the high potential of wind energy is available, particularly, in the Arctic region [1].

METHODS

Given the equipment composition and operating mode requirements, the international practice breaks down wind-diesel power plants into three groups, depending on the fossil fuel substation extent (see Table 1):

• small substitution systems;
• medium substitution systems;
• extensive substitution systems.

Table 1. Extents of wind energy employment by wind-diesel power plants

Substitution extent	Equipment operation and its peculiarities	Substitution share, wind power plant, %	
		In terms of capacity	In terms of output
Small	A diesel power plant is in continuous operation. The operation of the wind-driven power plant de-loads the diesel power plant. A wind-driven plant covers a portion of the principal capacity. A wind-diesel power plant needs no automatic control system	Below 50	Below 20
Medium	A diesel power plant is in continuous operation. When the generation capacity of a wind-driven plant is high, secondary loads are added. A relatively simple automatic control system is needed	50…100	20…50
Extensive	A diesel power plant is off. Supplementary solutions are needed to maintain frequency and voltage. An intelligent automatic control system is needed	100…400	50…150

Given the high wind energy potential of the Arctic region, optimization and modernization of the power supply systems in operation, and the construction of new power supply facilities may be effectively implemented with the employment of hybrid power supply facilities using modular renewable energy sources, for example, if the module capacity of a diesel generator reaches approximately 250 kW and the capacity of a wind-driven plant, accommodated to the climate of northern Russia, reaches 50…100 kW.

Technological solutions applied to wind-driven power plants must take account of problematic delivery conditions, a short navigation season, and fast assembly solutions. Any construction process must be free from the use of heavy lifting-and-conveying machinery in the absence of a road network; machinery maintenance must be performed without the involvement of highly qualified specialists and it must be highly automated (inclusive of adaptive algorithms) and comprise a remote control/diagnostics system. These solutions must save expensive diesel fuel, brought from afar; therefore, they must be equipped with automatic control systems to provide for extensive diesel fuel substitution.

A model of an intelligent automatic control system has been developed and integrated into Arctic wind-diesel power plants. It maximizes power generation from renewable energy sources by virtue of dynamic power distribution between the elements of a power supply facility, which minimizes fuel consumption (with a potential for the complete shutdown of fuel-powered energy sources after the renewable energy sources have reached a sufficient capacity).

The following development principles underlie an intelligent automatic control system:

1) maximizing energy generation by wind-driven power plants in the real-time mode, saving the fuel designated for diesel power plants, and covering the required demand for energy;

2) remote monitoring of a wind-diesel generator's parameters and operating modes;

3) intelligent operational dispatching of the elements and systems of a power supply facility to assure maximal independence of its operation;

4) monitoring of the equipment condition; analyzing the statistical data on its operating modes and projecting wind patterns;

5) scheduling equipment operation, maintenance, risk assessment and prevention of accidents;

6) redundancy of the main controller of a wind-diesel power plant and an instrumentation and control system; in case of an accidental situation, a manual control mode must be available;

7) adaptability and 24-hour supply of energy, even if some generating elements (of a diesel power plant or a wind-driven power plant) are out of service [2, 3].

These principles were invested into a software and hardware module of an intelligent system, designated for conversion, control, and distribution of energy [4], which was designed and developed by the Centre for Research and Education "Renewable Forms of Energy and Generators" at the Peter the Great St. Petersburg Polytechnic University. This software and hardware module streamlines the processes of generation and consumption of electric energy and development of a microgrid (an intelligent electric microgrid) for an off-grid village [5, 6].

The concept of this software and hardware module is applicable to off-grid energy supply facilities comprising renewable energy sources, diesel power plants and solar photovoltaic systems, namely, wind-diesel power plants, solar photovoltaic systems/wind-driven power plants/diesel power plants, solar photovoltaic systems/diesel power plants, each comprising a diesel generator. This module maximizes energy generation from renewable energy sources by virtue of dynamic power distribution between the elements of a power supply facility, and, as a result, it minimizes fuel consumption (with a potential for the complete shutdown of fuel-powered energy sources after the renewable energy sources have reached a sufficient generation capacity).

The functional diagram of the electric circuit of the software and hardware module is provided in Figure 1 [7].

A general structural diagram showing power distribution inside an off-grid power supply facility, comprising renewable energy sources consolidated by the alternating current, is provided in Fig. 2 [8].

Module hardware comprises two power facilities responsible for the dynamic control over the power balance of the bilateral current converter and controllable ballast; controllers of the bilateral current converter and controllable ballast responsible for the automatic control over the constituents of a power supply facility and the main module controller responsible for high-level performance control.

The sources of power of an off-grid power supply facility are broken down in the software and hardware module into the following two categories:

1) primary sources of a power supply facility that set the frequency and voltage for an off-grid power grid:

• diesel generator (the main source setting grid voltage);

• bilateral current converter having battery units connected to it (in the operating mode of an independent inverter);

2) secondary sources, that get adjusted to the grid voltage and generate power for the grid:

• wind-driven power plants;

• solar photovoltaic systems.

A diesel generator (generators) is the main source of power within an off-grid power supply facility and a secure source of power in the long-term mode (if the fuel supply is available). The diesel generator is not considered as an active control element within the system of dynamic control, because it has an independent dynamic control loop that maintains the pre-set voltage and frequency values of a generator. Software and hardware module controllers automatically and remotely actuate and shutdown diesel generators using Modbus and Modbus TCP protocols or discrete relay signals.

Thanks to the operation of the software and hardware module all the diesel generators of the power supply facility may be shutdown, if the total power wheeled from S1 and S2 and averaged through time period T exceeds the total consumed power, while renewable energy sources are used to their maximal extent (thus, saving as much diesel fuel as possible). In this case, the bilateral current converter becomes the primary source, as it switches to the mode of an off-grid inverter and generates voltage for the grid.

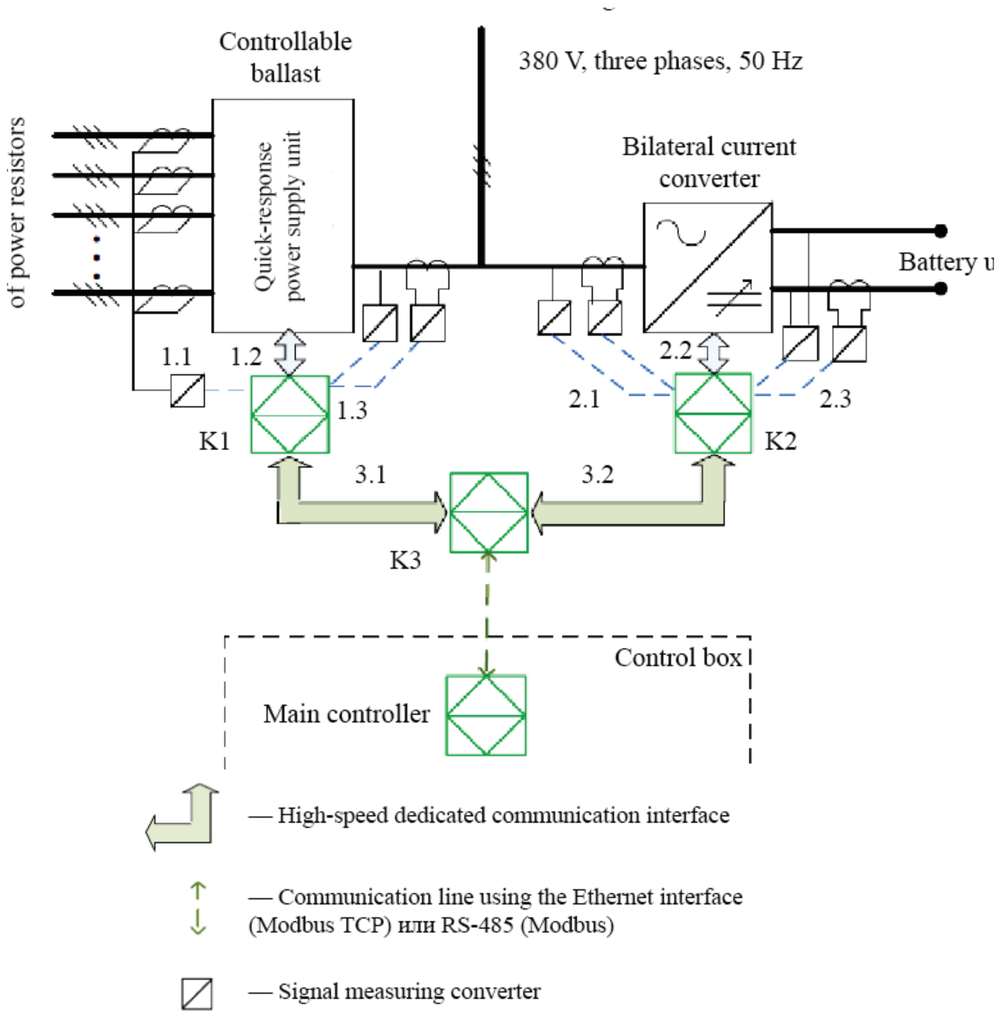

Fig. 1. Functional diagram of the electric circuit of the software and hardware module. K1 — controllable ballast controller; K3 — shared module controller; K2 — controller for a bilateral current converter; 1.1 — stage current control; 1.2 — circuits for the control and control of the ballast power contour; 1.4 and 2.1 — control and measurement of output electric parameters; 2.2 — circuits for the control and control of the internal power contour of the bilateral current converter; 2.3 — control and measurement of electric parameters of the battery unit

The total consumable power is determined as follows:

$$P_{tc}(T) = P_{pl}(T) + P_{sl}(T) + P_{ap}(T) + P_{max}(T), \quad (1)$$

where $P_{tc}(T)$ is the total consumable power, averaged through time period T; $P_{pl}(T)$ is the power consumed by priority loads and averaged through period T; $P_{sl}(T)$ is the power consumable by secondary loads and averaged through time period T; $P_{ap}(T)$ is the auxiliary power consumed by the power supply facility and averaged through time period T; $P_{max}(T)$ is maximal power set by the control system of the wind-diesel power plant for controllable ballast within time period T.

The control system of the software and hardware module shuts down the diesel generator and switches on to the bilateral current converter as the primary source if:

$$P_{rsp}(T) > P_{tc}(T) + P_{sc}, \quad (2)$$

where P_{rsp}(T) is the total electric power generated into an autonomous grid by all renewable energy sources of power (the total of S1 and S2), averaged through time period T; P_{sc} is the power safety corridor — a permanent value set by the personnel or calculated using the hardware and software projection algorithm (depending on its settings) [14].

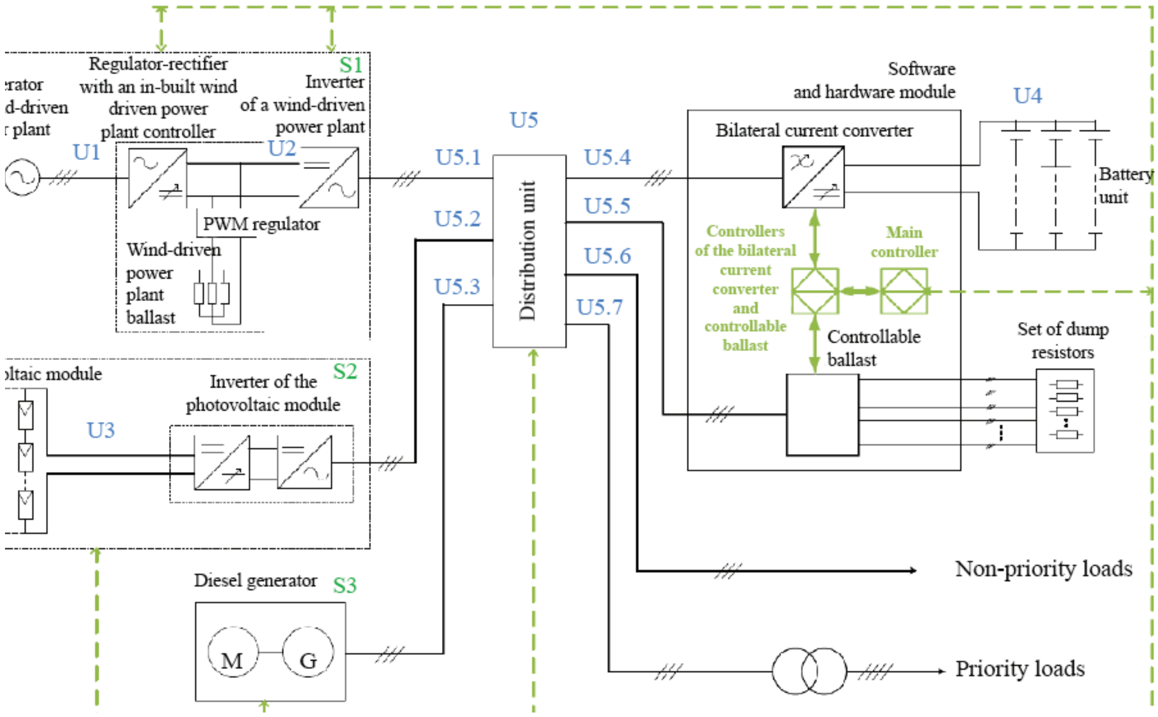

Fig. 2. General structural diagram of an off-grid power supply facility, comprising renewable energy sources and controlled by an intelligent power conversion/control/distribution system: ⟵⟶ — high-speed communication interface; ← – → — control links with remote units; wind-driven power plant; photovoltaic module; diesel generator; bilateral current converter; battery unit; controllable ballast; U1 — section of a circuit of alternating current having unregulated frequency and voltage; U2 — section of a circuit of direct current having unregulated voltage which is limited in terms of its top values; U3 — section of a circuit of direct current having unregulated voltage; U4 — section of a circuit of direct current where voltage is regulated within battery unit parameters; U5 — section of a circuit of alternating current where voltage and frequency are regulated (U5 is an autonomous grid)

In this mode, the bilateral current converter uses an external battery unit that operates in the cyclic charge/discharge mode, given the pre-set cyclic discharge value is equal to $\Delta W_{\text{cd\_bu}}$ (kWh). In order to understand the principle of operation of a bilateral current converter as part of the software and hardware module, it is important to know that a bilateral current converter, being the primary source of power, generates voltage (having a pre-set amplitude and frequency values) in an autonomous grid (if the diesel generator is idle) even when the battery unit is being charged (or when the grid power is consumed).

Therefore, a bilateral current converter that has a battery unit, continuously generates voltage in an autonomous grid in each of the following modes: while the battery unit is being charged, while the battery unit switches from the charge mode to the discharge mode, while the battery unit is being discharged, and while the battery unit switches from the discharge mode into the charge mode. This approach enables the independent operation of the battery unit within 5…10 minutes if the charge/discharge value is 10 % of the maximal consumable power value of the power supply facility. In other words, the operation of a power supply facility is feasible if the capacity of a battery unit is comparable with the nominal capacity of a battery unit used for the power supply of a diesel power plant in case of emergency. However, a battery unit must have a higher number of charge/discharge cycles available.

This mode is applicable concurrently with the operation of a diesel generator. In this event, the diesel generator operates as a secondary source and synchronizes with the bilateral current converter.

Bilateral current converter

A bilateral current converter is capable of converting the alternating current of an autonomous grid into the direct current of a battery unit, while power is wheeled from the grid to the battery unit (the battery charge mode) during the power consumption period. It is also capable of converting the battery's direct current into the alternating current, while power is wheeled from the battery into the grid (the battery discharge mode) during the energy production period. As indicated earlier, a bilateral current converter is used as a primary source when diesel generators are off and when the amount of power produced by renewable sources exceeds the amount of consumed power. The bilateral power converter employs an advanced design comprising a static inverter [9].

Secondary sources of power in the power distribution pattern of a software and hardware module

A **wind-driven power plant** comprises a wind wheel with a permanent magnet synchronous generator; a regulator-rectifier with a turbine controller (a nacelle) and controllable ballast; a grid inverter for a wind-driven power plant. The majority of producers offer this set of elements, and the capacity of a wind-driven power plant varies from 30 to 200 kW.

As for the operation of a grid inverter, it represents an inverter controlled by the grid. This inverter needs circuit voltage, that means that mass produced wind-driven power plants can only operate if circuit voltage is available (in case it is unavailable, wind-driven power plants shutdown in the protection mode entitled "loss of grid"). A diesel generator or a bilateral current converter generates voltage for an off-grid power supply facility.

A software and hardware module pre-sets and changes the following wind-driven power plant control parameters:

• pre-limiting the output power value;

• pre-limiting the intensity of a change in the output power value over time (dP/dt).

The software and hardware module treats the object of control as the source of power, that follows the grid, and its instantaneous power output is impossible to project and to regulate. However, the top value of the power output of a wind-driven power plant may be pre-limited for a definite period of time, and the intensity of a change in the output power value over time may also be pre-limited (dP/dt):

$$P_{\mathrm{wpp}}(t) = F\{V_{\mathrm{w}}(t);\ dP_{\mathrm{wpp}}/dt\} - P_{\mathrm{wpp\_lim}}, \tag{3}$$

where $P_{\mathrm{wpp}}(t)$ is the electric power output of a wind-driven power plant (the value of the instantaneous output power leaving the inverter of a wind-driven power plant); $V_{\mathrm{w}}(t)$ is the instantaneous value of the wind velocity; dP_{wpp}/dt is the maximal pre-set change in the power value of a wind-driven power plant over time; $F\{V_{\mathrm{v}}(t);\ dP_{\mathrm{wpp}}/dt\}$ is the function describing dependence of the maximal pre-set change in the wind power plant's output value on the wind velocity over time; $P_{\mathrm{wpp\_lim}}$ is the parameter limiting the top value of the output power pre-set in the wind-driven power plant (pre-set in the inverter of a wind-driven power plant). If this parameter is not applied, the capacity of a wind-driven power plant is limited by its maximal physical power, which is recognized in the function $F\{V_{\mathrm{v}}(t);\ dP_{\mathrm{wpp}}/dt\}$.

The number of wind-driven power plants within one off-grid power supply facility is not limited in the general case, as the source is controlled by the grid; therefore, in general, any number of sources, working in parallel, may be installed. Any necessary number of wind-driven power plants may be shutdown in response to a signal produced by the software and hardware module.

A solar photovoltaic system is similar to wind-driven power plants in terms of delivering power into an autonomous power grid. A grid-controlled inverter is the terminal device of a solar photovoltaic system (similar to the power-driven plant). Frequently, invertors of solar photovoltaic systems cannot limit the top value of the output power.

The software and hardware module treats the solar photovoltaic system as the object of control following the grid and producing power; its instantaneous capacity is impossible to project, and it is identified according to the following formula:

$$P_{\mathrm{wpp}}(t) = F\{E_{\mathrm{e}}(t)\} - P_{\mathrm{sps\_lim}}, \tag{4}$$

where $E_{\mathrm{e}}(t)$ is the solar radiation flux that reaches the module (W); $P_{\mathrm{sps\_lim}}$ is the parameter limiting the top value of the output power, this parameter is pre-set inside a solar photovoltaic system (inside its inverter). If this parameter is not applied, the capacity of a solar photovoltaic system is limited by its maximal physical power, which is recognized in the function $F\{E_{\mathrm{e}}(t)\}$.

The number of solar photovoltaic systems within one power supply facility is not limited in the general case, as the source is controlled by the grid; therefore, in general, any number of sources, working in parallel, may be installed [10].

The general condition, applied to dynamic power distribution in an off-grid power supply facility, consists in the power balance: the value of consumed power in the pre-set mode must be equal to the value of the power generated by the facility. The power balance guarantees frequency and voltage stabilization in an autonomous grid, and it is pre-set by the formula

$$P_{\text{total power}}(t) = P(t), \quad (5)$$

where $P_{\text{total power}}(t)$ is the instantaneous total value of power produced by all sources.

The software and hardware module, developed for the dynamic power distribution, objects of control are broken down into three groups:

1) actively regulated items;

2) items that are actuated automatically;

3) items that may be actuated or cutoff depending on power values.

RESULTS AND DISCUSSION

The methodology of intelligent control over off-grid wind-diesel power plants was integrated into the automatic control system of an autonomous wind-diesel power plant in 2017 to supply electricity to the village of Amderma (the Nenets Autonomous District). This project was implemented within the framework of the restructuring of a diesel power plant and the construction of a wind-diesel power plant.

Fig. 3. Wind-diesel power plant in Amderma.

This is one of the first power supply facilities, recently constructed in the Arctic permafrost area. The village has about 350 inhabitants; it is located on the shore of the Kara sea; the annual average/maximal wind velocity is 8/42 m/c; the minimal temperature is 42 °C; icings, intensive windstorms and snowstorms are frequent there. The following power generation facilities are in operation there: three diesel power stations, varying in terms of their capacities, their total output reaches 600 kW and four wind-driven power plants, 50 kW each. The altitude of each wind-driven power plant is 26 meters; they are made in China and adjusted to the local weather and climate pursuant to domestic engineering specifications. The design of this wind-diesel power plant comprises an original modular solution of the foundation that was developed for the permafrost area; it also boasts a self-lifting system that needs no crane [11].

The implementation of the wind-driven power plant and the construction of the wind-diesel power plant reduced:

• auxiliary power consumption from 510 thousand kWh to 160 thousand kWh (more than a three-fold reduction);

• diesel fuel consumption from 719 thousand liters a year to 416 thousand liters a year (by 40 %), which saves 12.5 million RR a year;

• CO_2 emissions by 600 tons.

The revenue generated by the reduction of the economically sound rate reached 45 million RR a year.

CONCLUSION

1. Given the features of its territory, physical and climatic conditions, socioeconomic peculiarities of its area and population, high energy rates in the areas of autonomous and decentralized power supply, a high potential of renewable energy sources, Russia has everything available for the development of energetically and economically effective technologies for energy supply to consumers using hybrid power supply facilities, comprising renewable energy sources.

2. The principles underlying the software and hardware module represent an intelligent automatic control system and a technological solution consisting in the dynamic power distribution inside an autonomous power supply facility based on the dynamic coordinated control over controllable ballast and bilateral power converter.

3. The control over a wind-driven power plant is limited to the adjustment of the maximal power value and/or maximal dynamic power value inside the inverter of a wind-driven power plant and a solar photovoltaic system during automatic switch-over to enable the use of mass-produced equipment for wind-driven, solar photovoltaic and diesel power plants.

4. By consolidating the sources and consumers on the side of the alternating current, the proposed and implemented principles, underlying the intelligent automatic control system of a wind-diesel power plant, make it possible to optimize power generation and consumption and to develop a MicroGrid for an isolated village.

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Received April 22, 2018.
Adopted in final form on April 29, 2019.
Approved for publication May 28, 2019.

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