

Stand-alone power supply system with DC photo-diesel source

Boris Lukutin¹, Dmitry Muravyev^{1*}

¹National Research Tomsk Polytechnic University, 30 Lenin Avenue, Tomsk, Russia

Abstract. An object of research is a diesel power supply system of the decentralized village of Tokma, Irkutsk Region, Russia. The objective is to increase the contribution of the PV part of a photo-diesel electrical system operating in parallel with a diesel power plant to a stand-alone distribution network of DC compared to parallel PV and diesel stations operating on AC; quality improvement and voltage stabilization in the electrical network; cost reduction of generated electricity. Optimization of the characteristics of a stand-alone power supply system at a DC is a difficult task, due to the impossibility of conducting tests in a real electric power system, and the use of physical modeling because of its extreme complexity. Given this fact, the task is to design software and hardware tools for optimizing the parameters of a DC photo-diesel power system. The developed models use MS Excel, MatLab/Simulink software packages, as well as weather data bases. A software tool has been developed that allows for simulation modeling of operating modes of photo-diesel power supply systems, generation, consumption and insolation level of a decentralized consumer, as well as determining rational technical and economic parameters; criteria of expediency and efficiency of constructing photo-diesel electric systems with DC have been identified. As a result, the level of voltage drop is reduced compared to the AC power supply system, the cost of 1 kWh of electrical energy is lower than in the AC power supply system, and the negative environmental impact is reduced.

1 Introduction

The overwhelming majority of decentralized power systems are built on diesel generators operating on AC. Diesel fuel for such generators is an expensive resource not always readily available in remote rural areas. The price of electricity for consumers in regions with a decentralized power supply is much higher than the price for those who are connected to a centralized network (approximately from 15 to 600 rubbles, as opposed to 0.97 to 8.2 rubbles per 1 kWh, respectively). Reasons for high electricity prices in regions with decentralized access are high transportation costs, escalating fuel prices, poor maintenance of generating equipment and variable load, which leads to inefficient conditions of operation of power equipment and significant losses of electricity.

However, the demand for electricity is growing as a result of the natural development processes of large areas with numerous dispersed settlements (for example, Russia and China). It is worth noting that in the international market energy prices fluctuate, and governments are increasingly forced to reduce dependence on fossil fuels (subsidize their high prices). The dynamics of the escalation of prices for diesel fuel in Russia is shown in Fig. 1.

Today, the real way to increase the energy efficiency of stand-alone diesel power supply systems are projects of local DC microgrids, where groups of AC power consumers are connected through autonomous inverters.

Generally, they include integrated renewable energy sources (RES), including PV modules, wind-electric installations with static converters of electrical energy parameters, accumulator storage systems, fuel cells, etc. The reliability of the distribution system of such projects is confirmed by the results of the research facility in the public network in Finland. This research facility was built and tested in a collaboration with the University of Technology Lappeenranta [1].

The hybrid structure combined with the nature of DC allows the use of intelligent control of intermittent renewable energy resources, power storage systems and diesel power plants (DPP) in order to reduce energy losses, improve energy quality, reduce fuel consumption and grid power compared to the hybrid AC power supply system. Creation of DC microgrid based on RES with distributed generation is one of the promising ways of expanding and diversifying the fuel and energy market of the states, pursuing energy security and independence [2].

When developing such projects, an important component is the requirement to analyze and, if necessary, revise the structure and technology of generation and consumption of a decentralized consumer. This can be done by mathematical modeling and subsequent feasibility analysis in software packages that allow for the simulation of the electricity system of a decentralized consumer, for example, the Simulink application in MatLab.

* Corresponding author: dim15@tpu.ru

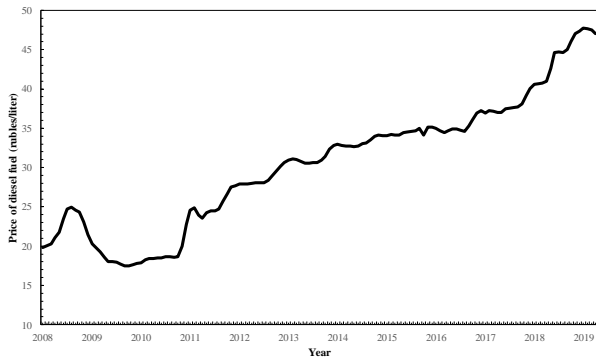


Fig. 1. Dynamics of diesel fuel prices in Russia.

The resulting models are structurally flexible: they are able to connect additional and independent sources of electricity, to identify sensitivity to external influences, such as ambient temperature and the level of insolation.

To achieve our goals, we chose a decentralized consumer with a DPP in the Irkutsk region – the village of Tokma. As of 2010, about 75 people live in the village of Tokma. This consumer has some obstacles for a stable and reliable power supply. According to the program of full development of the communal infrastructure systems of the Nepa municipality Tokma has the following characteristics of the power supply system [3]:

Table 1. Characteristic of the power supply system in the village of Tokma.

Diesel power station, kW		Power line length, m	
Unsatisfactory condition	Satisfactory condition	Unsatisfactory condition	Satisfactory condition
DPS-1 (30)	DPS-2 (60)	3000	1000

Climatic difficulties, inadequate characteristics of generating equipment, difficult transport conditions, support for a small ethnic group of residents, a development plan for the region, etc. – all these circumstances make it necessary to find a solution in a reliable and technically cost-effective implementation of the power supply system.

2 Methods and Methodology

In this article, the authors consider a single-phase hybrid power supply system consisting of a DPP, a PV plant, an electrical energy storage system, various types of consumers with variable load schedules, power transmission lines and insolation units with an ambient temperature. The SimPowerSystems library of the Simulink application was used for the simulation, and the block diagram in MatLab is shown in Fig.2.

In stand-alone power supply systems (SAPS), the voltage and consumption level are controlled by a reference source – a DPP with a voltage regulation system. In the DC power system, a diesel generator is connected to the distribution network through a semiconductor rectifier. PV modules are connected via converters [4,5] with the ability to track their maximum power depending on insolation and temperature conditions. According to its output characteristics,

distributed PV plants can be replaced with a DC source controlled by reference signal.

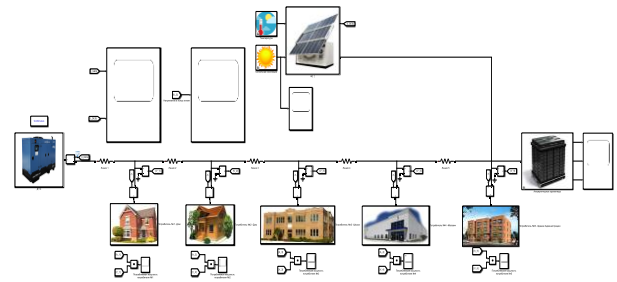


Fig. 2. Stand-alone photo-diesel DC system in MatLab/Simulink.

To analyze the quality of electricity in this SAPS, a series of numerical experiments were conducted with the following parameters of a PV plant for the summer and spring seasons; the slope of the receiving surface of the PV modules was 30° , for the winter and autumn season – 75° , the PV power station for all seasons is oriented in azimuth.

2.1 Diesel power plant

In the classical scheme of a DPP there are two automatic control systems: the automatic control system of the diesel engine frequency (output voltage frequency) and the automatic control system of the generator output voltage. The purpose of the first automatic system is to stabilize the speed of the diesel generator, and the second is to stabilize the voltage level of the generator.

For the purpose of modeling, the authors have equivalently used a DPP with a constant voltage source, which makes it possible to achieve an approximate excitation control of a synchronous generator. This operation was based on the works [4,5,6]. In Fig. 3 shows the equivalent of a DPP – a source of constant voltage.

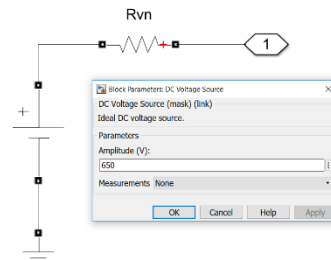


Fig. 3. Diesel power plant equivalent in the MatLab/Simulink.

Fig. 3 shows the parameters of a diesel power unit: an equivalent DC voltage source will be 650 V. The external characteristic of a real diesel power plant is taken into account by a series-connected resistance in a voltage source circuit.

2.2 Photovoltaic plant

The model of a PV plant is based on the output characteristics of the solar cell and simplified mathematical functions, which are represented as a block

of the subsystem. To build a model of a PV plant, the method proposed in [7] was used, according to which the maximum output power of a PV plant is determined by the expression:

$$P_{PV} = \frac{C_F \cdot N \cdot G \cdot \ln(10^6 \cdot G)}{T_{PV}}, \quad (1)$$

where N is the number of PV modules in the plant; C_F is a constant coefficient in the parameters of the PV module; G – current level of insolation, [W/m^2]; T_{PV} – current temperature of the PV module.

A PV power plant is equivalent to a controlled DC source that can be connected to various points in the network. An array of solar panels that make up the subsystem of a PV plant, transmit the generated current through a mains inverter, or directly into the network in the DC version. The influence of the solar controller is taken into account as a proportional decrease in the efficiency.

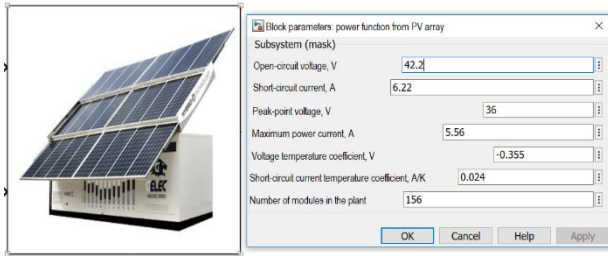


Fig. 4. PV station with input of parameters in MatLab/Simulink.

The internal parameters of the model are determined by the nomenclature data of the solar panel and their quantity. Input variables are the current values of insolation and temperature of the receiving surface. The simulation results showed that the developed model simulates the current characteristics of a PV plant with satisfactory accuracy.

2.3 Insolation and ambient temperature blocks

Most meteorological factors are stochastic. Currently, probabilistic methods for calculating radiation characteristics are dominant in the design of PV power plants. The magnitude of the primary insolation that enters the surface of a PV plant is determined by the intensity of the total radiation at its installation site. This value depends on the coordinates of the location of the PV plant, spatial orientation, as well as on external meteorological factors: air temperature, cloudiness level, earth surface reflection coefficient.

The basis of the calculation of this work is a technique that allows determining the hourly flow of insolation onto the inclined plane proposed by Liu and Jordan [8], which is determined by the expression:

$$Q_{incl} = S_{incl} + D_{incl} + R_{incl}, \quad (2)$$

where Q_{incl} – total insolation falling on an inclined surface [W/m^2]; S_{incl} – direct insolation falling on an

inclined surface [W/m^2]; D_{incl} – scattered solar energy falling on a sloping surface, [W/m^2]; R_{incl} – insolation reflected from the surface of the earth [W/m^2].

The set of mathematical equations for each of the parameters of equation (2) was determined in accordance with the works [4,8]. Data is entered into the MatLab subsystem-controlled block, shown in Fig. 5 for the modeling process: located in the high northern latitudes, which include most of the territory of Russia (Tokma village is located at 58° north latitude), external meteorological factors can have a significant impact on the characteristics of a PV plant.

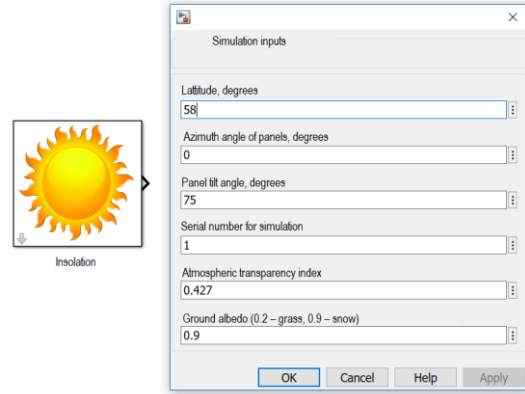


Fig. 5. Insolation unit with parameter input in MatLab/Simulink.

Monthly average and daily average values of ambient temperature are determined most easily. They are independent of the parameters of the designed electrical installation. The initial data for their determination are the statistical data of meteorological observations, which can be obtained from the archives of meteorological portals and climate guides. As part of this study, the authors introduce the daily mean temperature value, measured in Kelvin, as a block of constant.

2.4 Electrical energy storage system

To model the system for the storage of electrical energy, we use a method based on the generalized Shepherd relation, defined by the following expression [9] :

$$V_{SS} = E_0 - \frac{M \cdot Q}{(Q - \int idt)} - R \cdot i + A \cdot e^{(-B \cdot \int idt)}, \quad (3)$$

where V_{SS} – array voltage [V]; E_0 – no-load voltage of an unloaded array [V]; M – polarization resistance [Ohm]; Q – actual capacity of the array [A·h]; $\int idt$ – actual charge level of the battery array [A·h]; i – battery current [A]; R – battery internal resistance [Ohm]; A – coefficient characterizing the magnitude of the voltage drop during the exponential discharge zone [V]; B – coefficient characterizing the reciprocal of the capacity of the array at the end of the exponential discharge zone [$\text{A} \cdot \text{h}^{-1}$].

The main purpose of having batteries in a hybrid system is to increase reliability. This means that the system has extra energy. The block provides coordination of consumption and generation schedules by smoothing the output power generated at a specific time of the phase of the day from the PV plant. This principle allows to implement intelligent control between sources of electrical energy in this system.

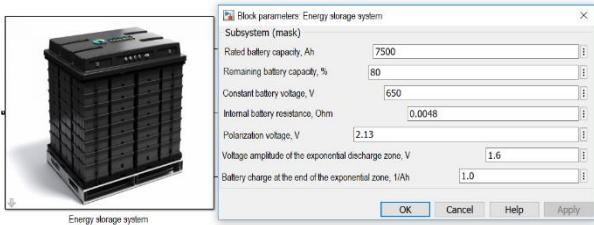


Fig. 6. Block energy storage system with the input parameters in MatLab/Simulink.

Inside the subsystem in Fig. 6, the simulation is carried out using a controlled voltage source connected in series with constant resistance, which takes into account losses. Entering the main parameters through the dialog box allows to manipulate the system parameters to study the characteristics of a SAPS, as well as to build models of PV power plants of arbitrary configuration.

2.5 Consumers and power lines

To simulate various types of consumers of decentralized facilities in rural areas, the indicators of values are determined in accordance with standard typical schedules of real electrical loads. The data of these graphs were obtained during statistical observations for the period from 5 to 10 years based on [10].

A consumer model is made on the basis of controlled keys in accordance with the division of time intervals during the day: morning, afternoon, evening, night with a switched value of active-inductive resistances. Consumers are connected through sections of supply lines with active-inductive parameters for the AC variant. For DC, the inductive component is absent in power lines.

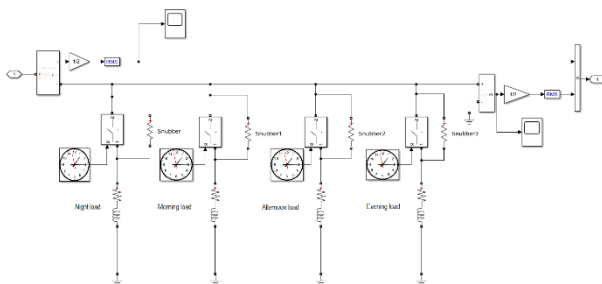


Fig. 7. Block of consumers of residential buildings in Matlab/Simulink.

The "Snubber" resistance block in Fig. 7 is necessary to suppress surges and vibrations when switching the "Ideal Switch" block in view of its modeling features: the block is programmed as a controlled current source.

3 Results

The indicators are divided into three groups, which have a significant impact on the decision making towards the development of a microgrid project based on a photo-diesel system and its transfer to DC. Groups are formulated as technical, economic and environmental benefits.

3.1 Technical benefits

Voltage deviations should not exceed 10% of the level established by State Standard [11]. The results of the study also show the amount of dissipative electricity in power lines. In Table 2, the results of intelligent control are aggregated, where *Mode I* – only the DPP is in operation, *Mode II* – the DPP and the PV plant are working, *Mode III* – the DPP, the PV power plant and the electric energy storage system are working. When a DPP operates without a PV power plant, we observe that the voltage level at the end of the transmission line is below the set threshold for all seasons of the year. Auxiliary power supplies in the form of a PV power plant and storage systems help to redistribute electricity in the energy balance.

Table 2. Technical indicators of the integration of a distributed PV power plant in a SAPS

Param.	Winter		Spring		Summer		Autumn	
	δU_y	ΔP_1	δU_y	ΔP_1	δU_y	ΔP_1	δU_y	ΔP_1
Mode I	25%	22%	21%	17%	19%	15%	23%	19%
Mode II	24%	21%	17%	15%	15%	14%	20%	18%
Mode III	4%	15%	7%	12%	7%	11%	8%	13%

In accordance with the intelligent control, the result is a change in the current value of the voltage drop (δU_y) at the end of the transmission line. Such integration reduces the power loss in the conductors (ΔP_1) and provides greater voltage stability at the points of connection of electricity consumers. This is achieved by connecting auxiliary energy resources at a distance from the DPP, which is at least half the total length of the power line.

The authors note that the efficiency of using PV power plants in SAPS using AC without energy storage systems is significantly limited by the operating conditions of network inverters. The reason for the "energy parity" of the generation of a PV plant in an AC system is the limitation of half the maximum power consumption of electricity [12]. *Mode II*, as can be seen from Table 2, makes an insignificant contribution to the technical performance of a DC power grid. There is a question of increasing the share of the contribution of intermittent energy resources to the energy balance of a SAPS with a business case. To stabilize the voltage in the power system and reduce power losses, it is advisable to use PV power plants with energy storage systems and connect them closer to the end of the distribution line or to the connection point of the most powerful consumer, as shown by *Mode III*. This control algorithm generated

from the electrical energy storage system during the hours of the morning and evening maxima, followed by the charge from the system of a DPP or a PV plant.

3.2 Economic benefits

A DC microgrid project will be economically feasible only if the estimated costs are comparable to the cost of fuel saved and the cost of reduced losses. The results of calculations based on modeling of diesel fuel consumption showed that the expected share of fuel economy will be 30~45% depending on the mode of consumption for the seasons.

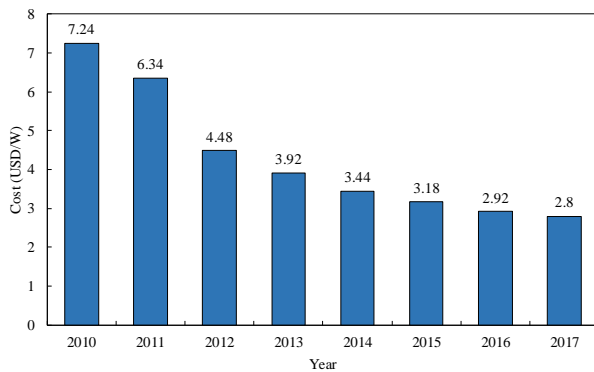


Fig. 8. Bar chart of power prices from solar generators around the world.

According to these data, it is necessary to recalculate the price of electricity supply from a DPP, where the current price for 1 kWh in the village of Tokma – 44.87 rubbles/kWh [13] is reduced by 12% against the price for AC (reduced by 8%). To calculate the tariff for the project of a microgrid on a DC using a PV plant and an electric energy storage system, the financial analysis model of investments in MS Excel was used.

Currently, the trend of falling prices for solar panels and the development of the market for distributed PV systems show that countries, administrative and municipal authorities are actively experimenting with policies aimed at encouraging distributed PV generation to compensate for peak electricity demand and stabilize the local grid stresses.

As shown in Fig. 8, in the period from 2010 to 2017, the cost of household PV systems decreased by 61%. Approximately 61% of this reduction can be attributed to the total equipment costs (module, inverter and system balance hardware), since module prices fell by 86% over this period of time. An additional 18% can be attributed to labor compensation, which over the same period has decreased by 73%, and the remaining 21% to other preferential expenses, including permits, checks and interconnections, sales tax, overhead costs and net profit. [14].

3.2 Environmental benefits

Energy production from burning fossil fuels results in emissions to the environment. Indeed, all means of

producing energy, including PV power plants, produce pollutants when their entire life cycle from creation to commissioning is taken into account. Life cycle emissions are the result of fossil fuel-based energy use.

To determine the amount of reduced emissions, the standard Russian method of specific diesel consumption was used. [15]. This standard indicates specific emissions per ton of consumed diesel fuel from diesel power plants.

Table 3. Environmental indicators of reducing emissions from a SAPS

Component	Reduction level, kg
Carbon dioxide (CO ₂)	374
Nitrogen oxide (NO _x)	425
Hydrocarbonates (C _x H _y)	190
Sulphur dioxide (SO ₂)	47
Soot (C)	39

As can be seen from Table 3, the integration of PV power plants with a system of storage of electric energy at a constant current in a SAPS leads to a reduction in emissions into the atmosphere every year by 6%, against 3.8% at an AC.

Integration of renewables in SAPS has not only a direct impact on reducing emissions. There is no doubt that indirect influence has no lesser weight: the reduction of production in the mining industry, the cost of liquid fuels, transportation costs, as well as rail or other methods of fuel delivery and transfer.

4 Conclusions

The software tool developed by the authors in the MatLab environment of the Simulink application allows simulation modeling of operating modes of photo-diesel power supply systems, generation, consumption and insolation level of a decentralized consumer, as well as determining rational technical and economic parameters; criteria of expediency and efficiency of construction of photo-diesel electric systems on a DC for power supply of remote consumers are fully revealed.

Authors were able to reduce the level of voltage losses in the DC power supply system as compared to the AC power supply system. The cost of 1 kWh of electrical energy is lower than in the AC power supply system with a difference of 4%, the negative impact on the environment is reduced.

The photo-diesel system on AC has a modest contribution to PV generation due to the condition of the limitation on the installed capacity of a parallel operating PV plant. The DC system is able to make a greater contribution of solar energy to the energy balance of a SAPS due to the simplicity of the realization of parallel operation of DC sources.

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