Optimization of isolated power systems with renewables and storage batteries based on nonlinear Volterra models for the specially protected natural area of lake Baikal

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Abstract. Lake Baikal conservation as UNESCO World Heritage property, national and international environmental laws dictate specific requirements and rules for the operation of energy facilities in the specially protected areas of Lake Baikal. Such restrictions have given particular strength to penetration of the renewables and storage systems. This article presents the universal method for optimizing the structure and installed capacity of isolated power systems using the example of a real tourist base. On the basis of the pool of mathematical models and control algorithms for power equipment the unified model of isolated power system was formed. The choice of mathematical models is made in accordance to the problem specifics and the climatic indicators. For optimal control of the processes of charging and discharging and determining the operating modes of the storage batteries the model based on nonlinear integral Volterra equations was used, which takes into account the nonlinear dependence of efficiency on the state of charge. In order to solve the problem of optimizing the installed capacity of the equipment the brute-force method was used. The results showed that the optimal use is polycrystalline solar panels with a total capacity of 60 kW and storage batteries with a capacity of 336 kWh.

1. Introduction
The current development of energy sector is characterized by high level penetration of renewable energy sources into centralized and autonomous energy systems [1]. The integration of renewable energy sources is observed at all voltage levels, starting with large power plants (high voltage level), small energy complexes of distributed generation (medium voltage level) and integrated micro-systems located at the consumer (low voltage level) [2]. Integration of large solar and wind farms into centralized energy systems makes it possible to reduce active power flows from neighboring energy systems, reducing the load factor on the traditional power plants, and increasing the power reserve of the microgrids nodes [3]. The construction of a small energy complexes of distributed generation concentrated in certain nodes of the energy system can increase the reliability indicators of power
supply to consumers, reduce of load factor in the power lines, and maintain voltage level in the distribution network [4, 5]. The development of the concept of integrated microgrids is caused by the desire of consumers to reduce their own annual fixed charges of purchasing electricity and to increase the reliability of their own power supply [6]. In addition, the improvement of arrangements for support renewable energy sources allowed the owners of such systems to sell electricity to the centralized network [7]. Thus, there is currently a rapid transformation of energy systems. In such conditions, the tasks of optimal development of energy systems are actualized. Traditionally, the tasks of operation include issues of static and dynamic stability of the energy systems with a high share of renewable generation and energy storage systems [8]. In the tasks of developing energy systems include the tasks definitions of optimal scheme and installed capacity optimization of power equipment and determining the technical and economic efficiency [9]. The development of legal tools to support of renewable energy sources creates favorable conditions for the comprehensive development of energy systems with renewable generation [10, 11]. Such support legal tools include feed-in tariff and green certificates. The feed-in tariff is a system for buying electricity from private producers, obtained from various renewable energy sources, including sun, wind, water and bio fuel. Thus, the government stimulates more active integration of advanced renewable energy technologies and creates favorable conditions for attracting investments in the energy sector. Green certificates are a financial and regulatory instruments used to support of renewable energy sources and clean energy producers. It is worth noting that certain restrictions may be introduced within the framework of a feed-in tariff or a green certificate, depending on the region in question. For example, generating facilities with an installed capacity of up to 50 kW (integrated micro-systems) can operate only within the framework of the feed-in tariff, while distributed generation facilities with a capacity of 50 to 500 kW already fall under the rules of the green certificate. It is important to note here the role of the regulator, which sets the boundaries within which generation facilities can function within a particular legal act. These boundaries should take into account the impact of integrated power micro-systems and distributed generation facilities on the safety and sustainability performance of centralized power systems.

The development of arrangements to support renewable energy sources creates favorable conditions for the comprehensive development of integrated/autonomous energy systems and distributed generation complexes [10, 11]. Renewable energy equipment production technologies have improved significantly over the past ten years. The presence of a competitive market has affected the cost of equipment and, as a consequence, it has led to change of the electricity levelized cost which is one of the main indicators. According to [12] the levelized cost of electricity for photovoltaic systems from 2010 to the present has decreased from $0.378 per kWh to $0.068 per kWh. At the same time, wind farms for the same period have values from $0.086 per kWh to $0.053 per kWh. The report [13] presents the dynamics of changes in the cost and efficiency of various types of storage batteries. The report says that the cost of storage batteries by 2030 will be reduced in the range from 50% to 65% depending on the technology [13]. At the same time, the technical indicators of storage batteries will improve, which are responsible for reducing the degradation of the active mass [14]. For example, the maximum number of charge / discharge cycles depending on the depth of discharge. Improvement of storage batteries technologies allows to reduce the cost of energy storage, thus creating favorable conditions for the large-scale use of storage batteries [15]. Thus, at present, favorable conditions are being formed both on the part of legal acts for supporting renewable energy sources and the cost of equipment.

2. Analysis of natural and climatic factors

Getting the initial climate information is an important step. Climatic indicators are necessary for correct modeling of solar panels, wind turbines and electrical load. In this study, multi-year meteorological datasets of the FM 12 Synop and METAR format are used. The studies provide a detailed description of the methodology for processing multi-year meteorological datasets and modeling total solar radiation on horizontal and tilted surface [16, 17]. The advantages of using long-term meteorological series include the following: these series contain detailed climate information; discrete step is from 30 minutes to 3 hours; the number of years reaches from 15 to 20; multi-year meteorological datasets take into account the correlation with each other. Multi-year meteorological
datasets in FM 12 Synop and METAR code forms are processed line by line throughout meteorological measurements, and the multi-year chronology of climate events is established with a one-hour discrete step. The full description of the methodology for processing and automatically correcting erroneous measurements and for eliminating time gaps in measurements of multi-year meteorological data sets in FM 12 Synop and METAR code forms is given in [16]. A typical meteorological year is a set of meteorological data with values for each hour of the year for a given geographical location.

3. Equipment modelling for isolated energy systems

There are many models for solar panels, wind turbine, storage batteries, power electronics and other equipment known in various levels of detail. In this part of the article, only those models that meet the specifics of the problem are given. The level of detail for mathematical models depends on two indicators: data from a typical meteorological year and engineering constraints. In this paper, the authors provided a detailed overview of six different mathematical models for solar panels. As a result, it was concluded that the model presented in this study is adequate and detailed [18]. This model takes into account various meteorological parameters. This study uses a classic solar panel model. The generation (W) is determined at the first stage of solar panel modeling

$$P_{PV}(t) = \bar{I}_A(t) \cdot \eta(t) \cdot A \cdot k_L,$$

(1)

where $\bar{I}_A(t)$ is solar radiation incoming to the solar panel tilted surface, W/m$^2$; $k_L$ is coefficient considering power losses in diodes and taken to be 0.85-0.95 p.u. due to pollution; $A$ is solar panel area, m$^2$. Photovoltaic converter performance is recalculated according to solar radiation, ambient air temperature, solar panel operating temperature and wind speed. The following formula is used to make such recalculation (p.u.)

$$\eta(t) = \bar{\eta}[1 - \beta \cdot (T_{PV}(t) - 48)],$$

(2)

where the photovoltaic converter’s operating temperature is expressed as follows

$$T_{PV}(t) = T_A(t) + \frac{\bar{I}_A(t)}{k_0 + k_1 \cdot V_W(t)},$$

(3)

Here $\bar{\eta}$ is nominal value of the solar panel efficiency, p.u.; $\beta$ is temperature coefficient for silicon solar panel (0.004-0.006), p.u./°C; $k_0$, $k_1$ are Koehl correlation coefficients (30.02 and 6.28); $V_W(t)$ is wind speed on the surface of the Earth, m/s. Photocurrent (A) is calculated at the next stage

$$I_{PH}(t) = \frac{\bar{I}_A(t)}{1000} \cdot [I_{SC} + k_1 \cdot (T_{PV}(t) - 25)],$$

(4)

where $I_{SC}$ is short circuit current of solar panel, A; temperature coefficient for current $k_I$ is taken to be 0.004 p.u./°C. After determining output power and current values with regard to changing solar radiation and the solar panel operating temperature, it is possible to determine voltage (V)

$$U_{PV}(t) = \frac{P_{PV}(t)}{I_{PH}(t)}.$$  

(5)

Based on the operating parameters of the solar panels, the connection scheme of the solar panels in the solar battery is determined. The connection scheme of solar panels in the solar battery depends on two parameters: current and voltage. Current and voltage vary greatly throughout the year. In this case, the following patterns can be noted. For example, the current of the solar panel is highly dependent on solar radiation, while the voltage is practically unchanged. In this case, the voltage of the solar panel depends on the operating temperature while the current does not change. The connection of the solar
panels is carried out in series and in parallel (mixed connection), where the series connection increases
the output voltage, while the parallel connection increases the current of the solar battery. The number
of solar panels connected in parallel and in series depends on the technical limitations of solar inverter.
The solar inverter has a certain number of inputs that are characterized by maximum values of current
and voltage. Therefore, it is necessary to determine such a connection scheme of solar panels under
which these conditions will be observed. Article [3, 18, 19] presents an algorithm for calculating the
optimal connection scheme solar panels in a solar battery. Also in this article a technique for
determining the installed capacity of grid-tie inverters is presented. In order to define alternating
power function (APF) and state of charge (SoC) for storage system we use Volterra models. The
Volterra equation is of course the classical problem, which has been intensively studied during the last
century. For systematic studies of Volterra integral equation of the first with discontinuous kernels
readers may refer to book [20]. Such Volterra models can be employed to simulate the degradation
processes in storage systems of grids using retrospective time series of generation and load for specific
location. As shown in [21], the calculation results for the Volterra energy storage model based on
nonlinear equations

\[
\begin{align*}
&f_i(t) = \int_0^t h_i(t, \tau, x_1(\tau), x_2(\tau), ..., x_n(\tau))d\tau = f_i(t), \\
&h_i(t, \tau, x_1(\tau), x_2(\tau), ..., x_n(\tau))d\tau = \left\{ \begin{array}{ll}
K_{i,1}(t, \tau)G_{i,1}(\tau, x_1(\tau)), & t, \tau \in p_1 \\
&... \\
K_{i,n}(t, \tau)G_{i,n}(\tau, x_n(\tau)), & t, \tau \in p_n,
\end{array} \right.
\end{align*}
\]

(9)

allow us to obtain a more accurate value of the state of charge for the energy storage and alternating
power function in comparison with the linear Volterra model, which was verified based on the
conventional linear model [27]. Here:

\[
p_i = \{t, \tau | a_{i-1}(t) < \tau < a_i(t)\}; a_0(t) = 0, a_n(t) = t, i = 1, 2, ..., m.
\]

(10)

where \(m\) is number of grids; functions \(a_i(t)\) show the proportions in which units in storage system
are used in each grid (for example, if grid has three batteries used in equal proportions, then \(a_0(t) = 0, a_1(t) = t/3, a_2(t) = 2t/3, a_3(t) = t\); \(n\) is number of units in storage system for \(i\)-th grid; the
diagonal elements of the matrix \(K[m \times m]\) shows efficiency of storage system of grid, the
remaining elements of the matrix show the coefficients of power flow from storage systems of other
grids; the efficiency of each battery nonlinearly depends on the time \(t\) and the function \(x_j(\tau)\), this
dependence is reflected by the functions \(K_{i,j}(t, \tau)\) and \(G_{i,j}(\tau, x_j(\tau))\) respectively; \(f_iRES(t)\) is
the generation of renewables presented in formula (6); \(f_{LOAD}(t)\) is predicted electric load of the
customers, \(f_{AC\&DC}\) is interconnection AC/DC power flow between grids; \(v_{i,\text{max}}\) is maximum speed of
the charge for \(i\)-th storage; \(E_{\text{min}}(t), E_{\text{max}}(t)\) are constraints on the storage levels. APF based on
\(x_j(\tau)\) is possible to find for each storage using proposed model. To find unknown functions \(x_j(\tau)\) we
use the efficient numerical methods of collocations for solution of the weakly regular nonlinear
systems of Volterra integral equations of the first kind [21–23], also Taylor-collocation methods [24,
25] can be applied. The existence of a continuous solution depending on free parameters and sufficient
conditions for the existence of a unique continuous solution of the systems Volterra integral equation of
the first kind with discontinuous kernels were derived in [26].

The diesel generator simulation should take into account the technical limitations of the diesel
engine used. In work [38], authors presented a universal model of a diesel generator based on the
universal speed characteristics of a diesel engine. This model allows you to take into account the change in load, rotation speed, and specific consumption of diesel fuel. In addition, this model is built in adherence to the technical limitations associated with the minimum allowable load factor. Figure 1 shows a simplified scheme of an isolated photovoltaic system with storage batteries and a diesel power plant.

![Figure 1](image_url)

**Figure 1.** Schematic representation of an isolated photovoltaic system: PV is photovoltaics; INV_s is solar inverters; DG is diesel generators; Load is electrical load; INV_b is battery inverters; SB is storage batteries; MS is management and control system

Isolated photovoltaic system operates according to the following algorithm:
1. If the generation of the photovoltaic system exceeds the electrical load, then the consumer is supplied with power and the batteries are charged.
2. If the generation from the photovoltaic system is less than the electrical load, then the consumer is supplied, and the energy deficit is extracted from the storage batteries.
3. If the state of charge of the storage batteries is less than a critical value, the diesel power plant is switched on. The diesel power plant directly supplies the electrical load and charges the storage batteries. This is a classic photovoltaic control algorithm

### 3.1. Optimization problem

In order to solve this problem, a brute-force search method is used. The optimization algorithm consists in a sequential enumeration of the installed equipment capacities. The levelized cost of energy (LCOE) is used as an objective function

\[
LCOE = \frac{\sum_{t=1}^{T} \left( K + M_F + F \right)}{\sum_{t=1}^{T} W 
(1 + \tau)^{T-1}}
\]

where \( K \) is the investment, RUB; \( M \) is annual expenses for equipment maintenance, RUB; \( F \) is annual fuel costs, RUB; \( \tau \) is discount factor, % (7% for Russia). The problem of determining the optimal technology is formed as follows

\[
\text{min } LCOE(K, M, F)
\]

under conditions

\[
y_{\text{grid}} = \xi_{\text{grid}}(P_{\text{PV}}^{\text{ins}}, P_{\text{INV_s}}^{\text{ins}}, P_{\text{INV_b}}^{\text{ins}}, Q_{\text{SB}}^{\text{ins}}, V_{\text{grid}})
\]

where \( y_{\text{grid}} \) are the installed capacities of solar inverters, battery inverters, storage batteries, electrical cables and other electrical network equipment; \( \xi_{\text{grid}} \) is a logical-numeric operator (a system of logical conditions and functional dependencies) that allows to determine the installed capacities of network
and auxiliary equipment for given standard sizes and installed capacities of photovoltaic system and storage battery capacity; \( V_{\text{grid}} \) is vector of typical sizes of network equipment.

\[
\begin{pmatrix}
P_{PV}(t) \\
P_{DG}(t) \\
Q_{SB}(t) \\
P_{S}(t)
\end{pmatrix} = R
\begin{pmatrix}
P_{\text{ins}}^{PV} \\
P_{\text{ins}}^{GIN} \\
P_{\text{ins}}^{BIN} \\
Q_{\text{SB}}^{ins}
\end{pmatrix}, \quad t = 1, ..., 8760,
\]

where \( R \) is a logical numerical operator that determines the operating parameters of the elements of the isolated energy system at the moment, depending on the installed capacities and technical limitations. Later determined annual generation figures, consumption of diesel fuel and other costs.

4. Object of study

As an example, a real tourist base located on the territory of Lake Baikal is presented. This tourist base is located in a hard-to-reach place, which can only be reached by ship or helicopter. The tourist base operates throughout the year. The tourist base is designed for 75 people. Three diesel generators (70, 50 and 40 kW) provide power supply. The cost of fuel, including delivery, is 60 thousand rubles per tonne. Currently, the number of years of meteorological observations is 10. The resulting array has the dimension 18×45786. Figure 2 visualizes the meteorological data sets.

Figure 2. Visualization of multi-year meteorological data sets

The area under consideration has a high photovoltaic potential, while the wind energy potential is very low. These conclusions are confirmed by the data of the National Cadaster of Wind Energy Resources of Russia. In addition, this once again confirms that multi-year meteorological datasets are accurate information. This study uses a real electrical load. This load was obtained as a result of processing the electronic operational log of the diesel power plant. This electronic log records the number of the diesel generators in operation and its electrical load every hour. For solving the problem of optimizing the installed capacity, polycrystalline and monocrystalline solar panels are used. The study uses OPzS storage batteries. This type of storage battery is well suited for isolated energy systems in Siberia and the Russian Far East.
5. Numerical results
As a result of solving the optimization problem, 183 options were compiled. The installed capacity of the photovoltaic system is considered in the range from 20 to 150 kW while the batteries are from 336 to 960 kWh. Figure 3 shows the optimization results. From the results obtained, it can be seen that the optimal value of the photovoltaic system is 60 kW, and the battery is 336 kWh. The installed capacity of solar inverters is 75 kW (3 x 25). Table 1 shows the main technical parameters of the obtained optimal solutions for monocrystalline and polycrystalline solar panels. The obtained solutions are equivalent. However, the option with polycrystalline solar panels is preferable due to the lower levelized cost of energy.

Figure 3. Optimization results

Table 1. Techno-economic indicators for the two composition arrangements.

|                        | Mono | Poly |
|------------------------|------|------|
| Installed capacity of PV, kW | 60   |      |
| Installed capacity of batteries, kWh | 336  |      |
| Quantity and capacity of solar inverters, pcs and kW | 3 x 25 kW | 75 kW |
| Quantity and capacity of battery inverters, pcs and kW | 3 x 30 kW | 90 kW |
| Capital investment, RUB mln | 15.51 | 14.91 |
| Annual expenses, RUB mln | 0.25  | 0.24 |
| Fuel consumption, tons/year | 19.94 | 20.79 |
| Fuel savings, tons/year | 33.31 | 32.46 |
| Direct supply in a solar power station, ths kWh | 53.70 | 51.35 |
| On battery charge, ths kWh | 22.23 | 20.70 |
| Power generation in a solar power station, ths kWh | 75.93 | 72.05 |
| Power generation in a diesel power station, ths kWh | 90.96 | 94.83 |
| LCOE, RUB/kWh | 16.90 | 16.83 |
| LCOE_DG (Diesel only), RUB/kWh | 29.42 |      |
6. Conclusions
In this study the specially protected natural area of Lake Baikal was considered, where the usage of renewable energy sources and storage batteries is relevant. The special status of this location forms a number of specific requirements and rules for the operation of critical infrastructure, incl. energy, objects. The integration of renewable energy sources in this location is economically and environmentally justified in the current legislative environment. The methodology for optimizing the installed capacity of renewable energy sources, storage batteries and power electronics is presented. The discreteness of the optimization parameters is due to the characteristics of the used equipment. In addition, the discreteness depends on the methods of connection (solar and storage batteries), taking into account the technical limitations of power electronics (solar and battery inverters). The brute-force method was used to solve the optimization problem. The target function is the levelized cost of energy, which allows one to take into account various economic variables (investment, fixed and variable costs), technical (generation, modes of operation) and various kinds of uncertainties. The method of generating a typical meteorological year based on publicly available long-term meteorological series data is used. Unlike various open source databases, this method allows us:

- To get a detailed description of natural and climatic indicators at specific location. The dimension of such arrays of climate information is almost 20 parameters. These arrays consist of numerical measurements and qualitative (verbal) assessment of cloudiness, cloud composition and bad weather clouds.
- To reveal the hidden climatic patterns at specific location and to form the most preferable options for the layout of isolated power systems with renewable energy sources.
- To more accurately model the modes of operation of the elements of isolated energy systems. For example, all the required data for a typical meteorological year is used in the solar panel model presented.

The pool of mathematical models assumed by the authors satisfies the specifics of the problem being solved. These models make it possible to take into account in detail the operating parameters of solar panels. The operating parameters of the storage batteries were obtained by the Volterra model. This model, in contrast to the generally known ones, allows one to take into account various nonlinear processes, such as a decrease in available power, efficiency and degradation. Also, the considered model based on nonlinear Volterra integral equations allows one to determine storage battery operation modes for the following cases:

- Two or more types of storage batteries for each isolated energy system.
- Two or more isolated energy systems with a different composition of equipment for storage systems and renewable generation.

Solving the problem of optimizing the installed capacity for the tourist base located in a specially protected natural zone of Lake Baikal showed the following results:

- The optimal value of the installed power of the photovoltaic system is 60 kW for both polycrystalline and monocrystalline solar panels.
- The savings in diesel fuel are 60.9% compared to a diesel power plant alone.
- Levelized cost of energy is 16.83, which is 43% less compared to a diesel power plant.

Acknowledgments
The reported study in Sections 1–3 was funded by RFBR and NSFC according to the research project No. 19-58-53011/61911530132. The reported study in Sections 4 and 5 was funded by RFBR and the Government of the Irkutsk Region, project number 20-48-383004.

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