Method for selecting parameters and assessing efficiency of wind-diesel power plants for autonomous electrical supply systems

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Abstract. The article presents an original technique for selecting parameters and evaluating the efficiency of wind-diesel power plants for isolated power supply systems. The initial data to perform energy calculations are simulation models of electric load and wind speed. The load is simulated using typical schedules of electric loads of a decentralized consumer, taking into account a random component for each hour of the day. To create a simulation model of the wind, a typical climatic series of wind speeds at a prospective site of the power plant has been constructed according to the data of long-term meteorological observations. The proposed technique was verified through the example of choosing a wind-diesel power plant for the village of Ust-Olenyok of the Republic of Sakha (Yakutia).

1. Introduction

The problem of power supply to the Northern territories has been, for many years, crucial to Russia. Electricity cannot be delivered to consumers living in the Northern territories through the central electric network due to huge distances and low population density, and the only source of electricity available for these territories is diesel power plants (DPP). High depreciation of the main generation equipment and serious problems in the fuel delivery result in a less reliable electricity supply to consumers and a higher cost of electricity produced. The so-called *Northern Deliveries* program involves annual transportation of up to 6–8 million tons of combustive-lubricating materials, and the share of transport component goes up to about 70% of the total cost of fuel [1]. As a result, the power supply to the Northern territories requires significant financial expenses from the federal and regional budgets.

Meanwhile, the Northern territories of Russia have a huge renewable energy potential that can be used to improve the reliability of power supply and to reduce the cost of electricity. For example, the annual average wind speed along the entire Arctic coast of Russia is 6–7 m/s, which enables using wind-diesel power plants (WDPP).

The study aimed to develop the method for selecting parameters and assessing efficiency of wind-diesel power plants for autonomous power supply systems. The proposed method was verified through the selection of a suitable WDPP for the village of Ust-Olenyok, the Sakha Republic (Yakutia).

2. The object of the study

The The scheme with generation units connected to the DC bus was chosen as a basis for the WDPP construction, since it provides the efficient control of operating modes of autonomous power supply

systems with a high replacement level [2, 3]. Figure 1 presents a generalized structural diagram of the WDPP adopted for the study.

In general, WDPP comprises two main generation sources: diesel generator sets (DGS) and wind turbines (WT). Rechargeable batteries (RB) are responsible for supplying electricity to consumers during a shortage of electricity generated by wind turbines. All generation sources are connected to the DC bus via semiconductor power converters controlled by the operating system (OS). The consumer is connected to the DC bus through the autonomous inverter (AI), which provides the conversion of DC to AC with standard parameters. To discharge surplus power generated by wind turbines in strong wind and light load, WDPP provides ballast load (BL), which is the heating elements, and ballast regulator (BR), which changes power consumption.
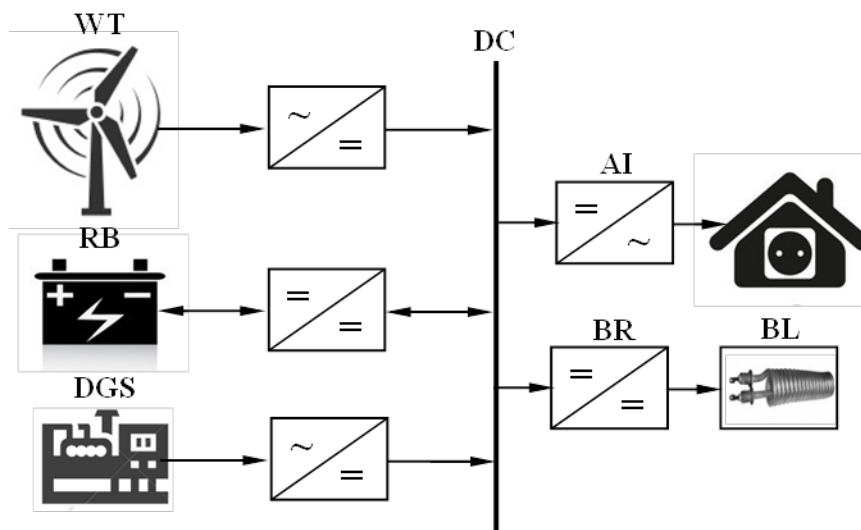
Figure 1. A generalized structural diagram of WDPP.

In addition, RB is equipped with a residual capacity monitoring device. In accordance with the limit set points of the monitoring device, the OS generates control signals to ensure charge/discharge modes for the battery converter.

3. Modeling of the object of the study

The power efficiency of WDPP largely depends on the parameters of the main generation equipment, which should be selected with regard to the characteristics of wind regime at the power plant site. Mathematical modeling was used for studying the power system due to the nonlinear parameters of its main elements and the complexity of physical processes. Simulated models of power load and wind speed are the initial data for the power calculations.

The load is modeled on the standard load schedules for a decentralized consumer with regard to a random component for every hour of the day [4].

A standard wind speed sequence at the considered power plant site is constructed to create the wind model. The data on long-term meteorological observations of the wind speed at the nearest meteorological station are used for the construction of a standard climate sequence [5, 6]. Since the data on the wind speed available on the free-access meteorological sites are averaged over 3- or 6-hour time periods, the original number series is transformed into the annual series with hourly sampling, taking into account a random component.

The method for calculating the fuel consumption at the DGS under different load conditions is based on specific fuel consumption rates for diesel power plants. The operational characteristics of the wind turbine are used to determine its output power [7].

The simulated model enables a comprehensive assessment of the power efficiency of WDPP and optimization of its main generation and storage equipment for a particular power plant.

4. Results of the study

The WDPP located in the village of Ust-Olenyok, the Sakha Republic (Yakutia), was used to verify and improve the simulated model. To date, power supply to the village is provided by the DPP. According to available statistics, in 2015 specific fuel consumption was 560 g/kWh. The village is situated on the Arctic coast, in the zone of strong winds and, according to preliminary estimates, this creates good prospects for using wind turbines. Consider three possible options for the construction of autonomous power supply systems:

- based on DPP;
- based on DPP and WT;
- based on WDPP with a battery storage.

The standard daily load schedules were modeled for Ust-Olenyok in compliance with the seasons of the year to choose DPP that comprises two DGS with the nominal power of 12 kW and specific fuel consumption of 314 g/kWh [8]. The results of calculating the energy characteristics of WDPP were analyzed to determine a rational number of the required batteries, which are based on gel batteries Haze HZY 12 230 [9].

The WT models by FD [10] were used for the comparative analysis of power and technical and economic characteristics of WDPP, and WT of different power classes. The choice of the brand is due to the fact that its inexpensive and reliable models with a horizontal axis of rotation are offered for sale by numerous sales representatives in Russia. The FD brand offers models of the entire power range required for a low-power WDPP. A detailed specification for the supplied power equipment is provided on the manufacturer's website.

A mathematical model of WDPP is a simulated model, therefore the energy characteristics were calculated in series of 6 experiments, with unchanged initial data and subsequent averaging.

For the considered options of the construction of autonomous power supply systems, the annual average electricity consumption was 28345 kWh, and the winter maximum load was equal to 10.5 kW.

For the power supply systems based on DPP, the annual fuel consumption was 12.030 kg, with the average specific consumption of 425 g/kWh. In this case, the annual number of operation hours for DGS will be 8.760 hours. Wind turbines operating together with diesel power plants will enable a partial replacement of diesel fuel used to generate electricity. The number of operating hours for DGS will be reduced as well. This will prolong the operational lifetime of diesel generator sets.

The power efficiency of wind turbines is estimated by the capacity factor *CF*, which is defined as a ratio of the actual (calculated) energy produced by WT W_{actual} over a certain time interval to the energy that can be produced by WT running at the rated power P_{WT} over the same time interval. For a time interval of 1 year, *CF* values are determined by the Equation:

$$CF = \frac{W_{actual}}{8760 \cdot P_{WT}} \qquad (1)$$

The capacity factor depends mainly on the WT quality and the characteristics of wind regime at the WT site. The energy efficiency factor *EEF* provides a more precise assessment of the WT power efficiency. *EEF* is defined as a ratio of the energy consumed W_{load} to the total amount of energy produced by WT W_{actual}:

$$EEF = \frac{W_{load}}{W_{actual}} \qquad (2)$$

EEF values enable estimation of the quantitative contribution of WT to the power supply. Figure 2 shows the calculated dependences of the energy characteristics of WDPP without RB depending on the installed power of WT.
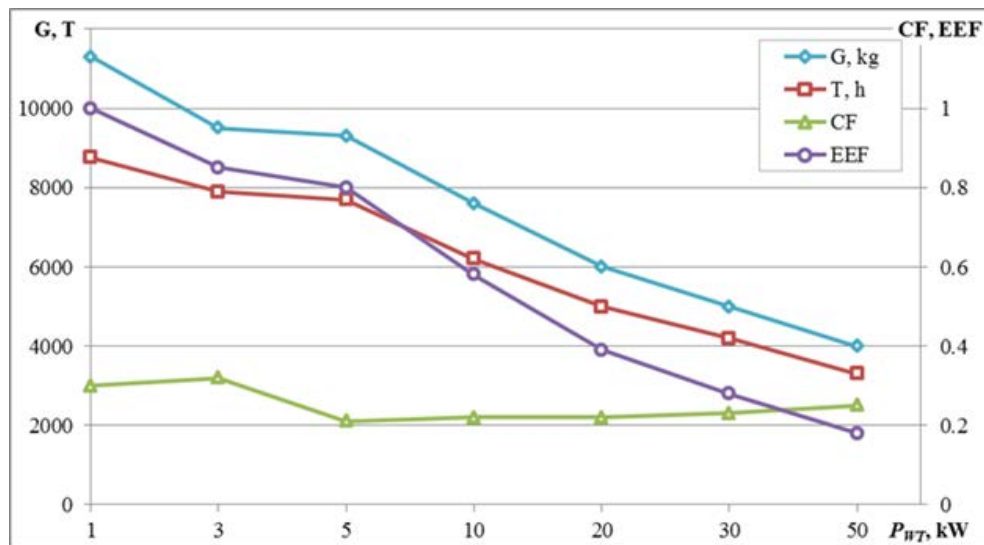
Figure 2. Energy characteristics of WDPP without RB.

The calculated dependencies show that the WT operating as a part of the power plant contributes to the improvement of the plant energy characteristics. An increase in the installed power of wind turbines leads to a reduction in both the total fuel consumption G and the operating hours of the diesel generator T. However, the energy efficiency factor EEF decreases as the WT power grows. EEF for the WT with a rated power of 1 kW equals 1.0, which indicates that the energy generated by WT is usable; EEF for the WT with a rated power of 50 kW is equal to 0.16, which indicates that more than 80% of the energy produced by WT will be dissipated on ballast resistances.

Meanwhile, the cost of WT with a power of 50 kW is much higher than that of 1kW. Therefore, it is necessary to find the optimal ratio of the installed power for DPP and WT, which will ensure a rational EEF for wind turbines at acceptable costs. In this case, the criterion for the optimal solution is the following economic indicators: annual costs, net present value, net cost of kWh of electricity, etc.

The disadvantage of the WDPP without RB is the increased operating time of the diesel generator for a low-power load. When the diesel generator is loaded less than 25% of the nominal load, the specific fuel consumption significantly increases, and the effect of carbonization caused by the accumulation of unburned fuel fractions in the cylinders can be observed. All these factors reduce the engine's life. The calculation results show that the joint operation of the WT and the DPP reduces the total operating time of the DGS, but it leads to an increase in its relative operating time under heavy operating conditions with a low load. For the considered example, the maximum relative operating time of the DGS under partial low-load conditions reaches 57% (for WDPP with a 20 kW WT).

The WDPP with RB enables an increase in EEF of WT due to the energy stored in the battery at the output power exceeding the consumed load, and significantly improves the operating conditions for diesel engines. The problem of the optimal battery capacity is crucial to be solved when designing the WDPP with RB.

Figure 3 presents the calculated dependences of the energy characteristics of the WDPP with RB depending on the number of batteries N in the WT with the installed power of 30 kW. The comparison of the characteristics of the WDPP with RB and those of the power supply system based on DPP and WT of the same power (see Figure 2) shows a significant improvement in the energy efficiency of the system.

If RB comprises 60 batteries (the total capacity is 144 kWh), there will be a decrease in the annual fuel consumption from 5.185 to 1.650 kg, and the annual number of operating hours of the DGS will drop from 4.325 to 490 hours. The positive effect is due to the increased EEF value from 28 to 38%. In addition, the number of operating hours of the DGS under a low load condition (with a high specific fuel consumption) is significantly reduced.
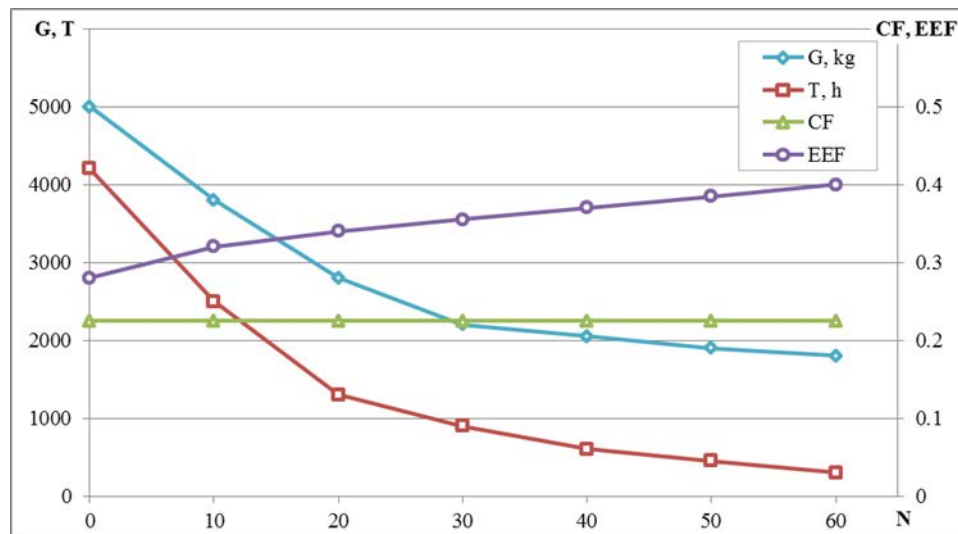
Figure 3. Energy characteristics of WDPP with RB

The results of the study show that the WDPP with RB allows minimizing not only the total number of operating hours of the DGS, but also ensures its optimal loading. The number of operating hours of DGS with a load of less than 25% will be only 40 hours for the WDPP with RB containing 60 batteries, which is less than 8% of the total operating time.

Figure 4 illustrates the daily operating mode of the WDPP based on DGS with a rated power of 12 kW, a 30 kW WT and RB containing 40 batteries with a total capacity of 96 kWh. The energy flows in WDPP are controlled by the OS.
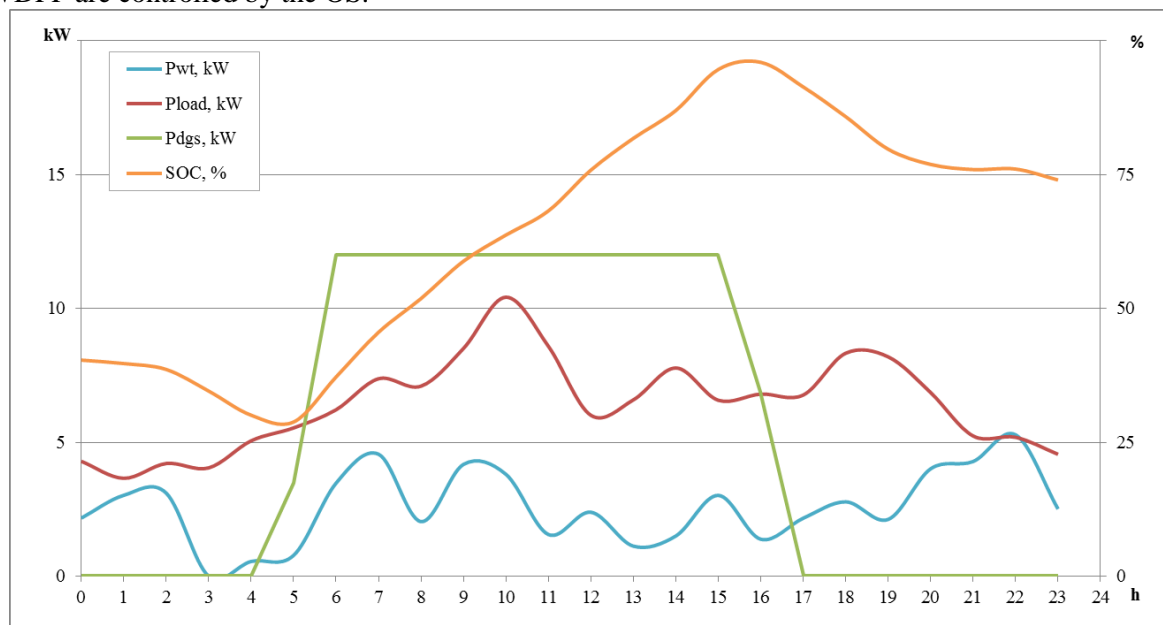
Figure 4. Daily operating mode of WDPP with RB.

Figure 4 shows a decrease in the RB residual energy down to 30% of the total capacity within the time interval 0–4 hour. The OS generates a signal to start the DGS, which, together with the WT, provides both the power supply to consumers and a full charge of the batteries within 5 to 16 hours. At the same time, the DGS operates in the optimal mode with a minimal specific fuel consumption. After 16 hours, the batteries are fully charged, the DGS switches off, and the load is supplied by the WT with RB within 16 to 24 hours.

5. Conclusions

The theoretical studies of the operating modes of the WDPP proved the possibility of improving the energy characteristics of autonomous power supply systems based on DPP: reducing the diesel specific fuel consumption, extending the life of diesel engines, and increasing the reliability of power supply to consumers.

The improved energy characteristics of the WDPP are due to a rational choice of the installed power of generation and accumulation sources, which are determined by the parameters of wind regime at the power plant site and the nature of electric load, and optimal control of energy flows in the closed energy system provided by a unified system for controlling operating modes. The rational ratio of the installed power for DPP, WT and RB is not standard, it is determined for each WDPP with regard to the specific conditions of its location and operation. Thus, technical and economic characteristics are appropriate to be used when choosing the main power equipment.

Acknowledgments

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