

# Simulation and optimization of wind and diesel power supply systems

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**Abstract.** The paper proposes an algorithm to optimize the structure and the choice of capacity of wind and diesel power units of the combined power plant, depending on the wind energy potential and electricity consumption of electrified facility. The algorithm is based on mathematical models of technical and economic characteristics of wind and diesel power plants as well as an optimization method of coordinate descent. The algorithm takes into account the structure of the combined power plant, changing modes of its operation, construction and operation costs of the power facility. The objective function of the algorithm is to minimize the cost of electricity generated.

## 1. Introduction

A large number of papers are devoted to the issues of simulation and optimization of the power supply system (PSS), using renewable energy sources (RES). Let us note the works [1-3], which significantly contributed to designing software packages for automatic optimization. The most common are as follows: HOGA – Hybrid optimization by the genesis algorithm (Spain), HOMER – Hybrid optimization modeling software (USA), HYPORA – Hybrid power optimized for rural / remote areas (USA).

Mathematical models of optimization software packages are implemented by various means of computer programming: C ++, MS, Excel, JAVA, etc.

The advantage of these optimization software packages is the possibility to solve optimization problems of power facility with an optimal ratio of generating units having different physical properties. The presented software packages feature a convenient interface, which simplifies their use.

Disadvantages of this software refer to the following restrictions:

- the wind energy potential is assessed based on the average annual or average monthly wind speed without taking into account its random origin;
- the lack of correlation between the parameters of the environment and the parameters of power equipment;
- inability to perform calculations and measurements of electric power losses in the power supply system;
- inability to perform investment detailing during the construction and operation of PSS;



- inability to change the structure of the combined power supply system and supplement it with new elements.

These restrictions do not allow optimizing the structure and parameters of wind and diesel PSS subject to a number of important characteristics of the system. These features include a smart interaction algorithm of PSS elements as well as technical and economic performance detailing of the system over the estimated period of operation [4].

The aim of the study is to develop a methodology in order to optimize the structure and the technical and economic characteristics of wind-diesel power plants.

## 2. Simulation and optimization of wind and diesel power supply systems

The process of choosing the best option - the minimum value of the optimization criterion, e.g., the cost of electricity, can be carried out by various methods, for example, the method of coordinate descent [5].

Let us assume that we need to find the smallest value of objective function  $u = f(M) = f(x_1, x_2 \dots x_n)$ . Here,  $M$  denotes the point of the  $n$ -dimensional space with coordinates  $x_1, x_2 \dots x_n$ :  $M = x_1, x_2 \dots x_n$ . Let us choose starting point  $M_0 = (x_1^0, x_2^0 \dots x_n^0)$  and consider function  $f$  with the fixed values of all variables, except for the first:  $f(x_1, x_2^0, x_3^0 \dots x_n^0)$ . Then it becomes a function of one variable  $x_1$ . Changing this variable, we move from starting point  $x_1 = x_1^0$  in the direction of decreasing the function, until we reach its minimum at  $x_1 = x_1^1$ , after which it begins to increase. A point with coordinates  $(x_1^1, x_2^0, x_3^0 \dots x_n^0)$  will be denoted by  $M_1$ , while  $f(M_0) \geq f(M_1)$ .

We fix variables:  $x_1 = x_1^1, x_3 = x_3^0 \dots x_n = x_n^0$  and consider function  $f$  as a function of one variable  $x_2$ :  $f(x_1^1, x_2, x_3^0 \dots x_n^0)$ . Changing  $x_2$ , we move from initial value  $x_2 = x_2^0$  again in the direction of the decreasing function, until we reach a minimum at  $x_2 = x_2^1$ . The point with coordinates  $(x_1^1, x_2^1, x_3^0 \dots x_n^0)$  will be denoted by  $M_2$ , while  $f(M_1) \geq f(M_2)$ .

We draw the same minimization of the objective function with variables  $x_3, x_4 \dots x_n$ . Reaching variable  $x_n$ , let us return to  $x_1$  and continue the process. This procedure fully justifies the name of the method. Based on it, we design a sequence of points  $M_0, M_1, M_2 \dots$ , which corresponds to a monotonic sequence of function values  $f(M_0) \geq f(M_1) \geq f(M_2) \dots$ . Breaking it at some point  $k$ , we can approximately assume the value of function  $f(M_k)$  to be its smallest value in this area.

Let us note that this method reduces the problem of finding the smallest value of the function of several variables to a multiple solution of one-dimensional optimization problems. The method is quite simple; however, taking into account the discrete parameters of power equipment, its capacity is sufficient for the given field of power engineering.

The main criteria of economic efficiency of wind and diesel power plants include the reduced annual costs of 1 kW of installed capacity of a power plant and the costs of 1 kWh of electricity. These criteria are determined by the following expressions:

$$C = \frac{P_n \cdot K + E}{P}, \quad (1)$$

where  $P$  – installed capacity of power facility (kW);  $K$  – total investment, which can be calculated using the formula:

$$K = K_{eq} + K_{de} + K_{con},$$

where  $K_{eq}$  – costs of complete plant equipment;  $K_{de}$  – design costs;  $K_{con}$  – costs of construction and installation of power plants (substations);  $P_n = \frac{1}{T}$  – norm coefficient of profitability,  $T$  – economic life of the equipment (years).

In formula (1),  $E$  – total annual operating costs, which can be calculated from the formula:

$$E = E_{op} + E_{main} + E_{fu} + E_{tr},$$

where  $E_{op}$  – annual costs of power supply system operation;  $E_{main}$  – annual maintenance costs;  $E_{fu}$  – annual fuel costs;  $E_{tr}$  – annual costs of fuel transportation.

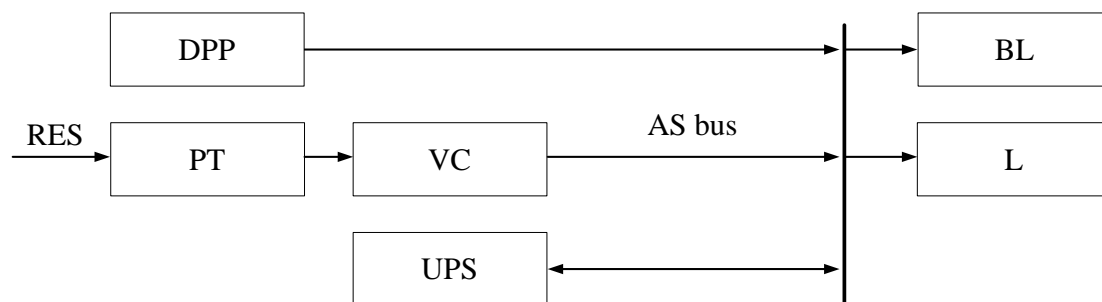
The prime cost of 1 kWh of electricity is:

$$E_{el} = \frac{P_n \cdot K + E}{W},$$

where  $W$  – total amount of electrical energy generated by power plants during the year.

Economic analysis of the stand-alone power supply, under existing economic conditions in Russia in this regard, can be aimed in many cases at reducing the subsidies cost. Accordingly, electricity production in decentralized power systems is often unprofitable. It is advisable to determine the norm coefficient of profitability in these situations based on the life of the main power equipment. Renewable energy sources and the smart energy system, under certain conditions, can improve the technical and economic characteristics of the stand-alone power supply systems [6, 7]. Given that the vast majority of existing power supply systems include diesel power plants (DPP), the possible increase of technical and economic indicators should start with an analysis of DPP operation modes.

The aim of optimizing the composition and operation modes of DPP is to reduce the fuel component in the electricity costs. Optimizing DPP load modes will increase the service life of diesel generators, and possibly reduce their installed capacity, which will decrease capital costs. The introduction of the wind power plant to stand-alone diesel PSS, under certain conditions, reduces the cost of electricity produced. Capability study for renewable energy integration into the stand-alone power supply system should start with analyzing the energy potential of renewable energy sources and, then, choosing a combined power plant structure [8]. Basically, combined power plants can be constructed both for separate operation of diesel and renewable parts or their parallel operation to supply stand-alone electricity consumers. A simplified block diagram of this facility is shown in Figure 1.



**Figure 1.** The simplified block diagram of the wind and diesel power plant.

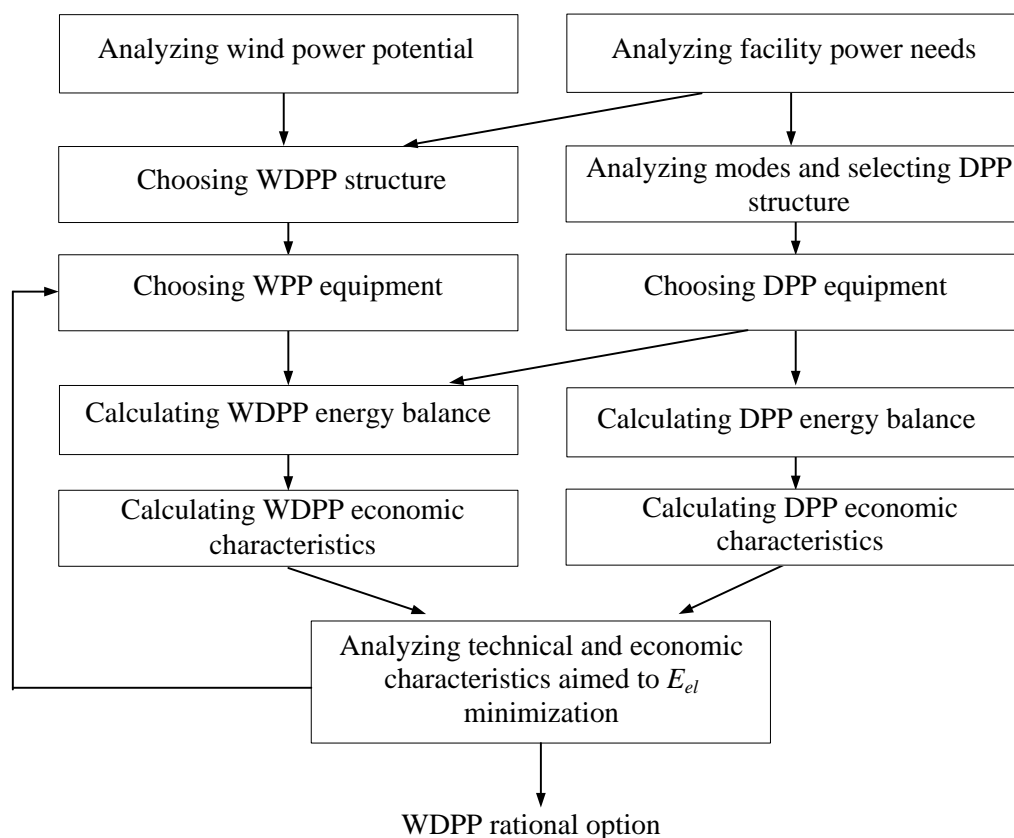
Figure 1 shows the following abbreviations: DPP – diesel power plant; PT – primary transducer of wind energy RES; VC – voltage converter; UPS – uninterruptible power supply; L – load; BL – ballast load. The combined operation mode does not require the use of UPS and BL, and is characterized by the low use of wind energy. The installed capacity of each independent energy source of the combined power plant with the separate operation mode of WPP and DPP should be capable of covering the electrical load of the system. Consequently, the available power of each energy source shall comply with the maximum power of the consumer. Available DPP power usually ranges from 0.7 to 0.8 of its installed capacity. The available capacity of wind power plants, in addition to the installed capacity, is determined by the wind energy potential.

Obviously, for the approximation of available WPP capacity to its installed capacity, it is necessary to choose a wind turbine with the rated wind speed close to the mean wind speed in the area of the

proposed windfarm installation. Increasing the installed capacity utilization factor of wind power improves its economic performance and, accordingly, technical and economic characteristics of the combined power supply system. For example, the cost of electricity generated by WPP depending on the average wind speed, other things being equal, is characterized by the following values: 7.16 m/s - 4.8 cents per kWh; 8.08 m/s - 3.6 cents per kWh; 9.32 m/s - 2.6 cents per kWh. It should be noted that the rated wind speed for wind turbines is commonly in the range of 10 – 15 m/s.

Therefore, combined wind and diesel power plants with separate operation of generating units are suitable for areas with high wind power potential to provide a large part of electricity generation for the consumer [8].

To ensure the quality of power supply and the maximum wind energy in these systems, uninterruptible power supply and ballast load are used. Stand-alone inverters are used for inversion of wind power parameters. From an economic point of view, WPP supplement to diesel power systems, designed to cover the electrical load for most of the time, requires considerable additional costs for the design and construction works as well as WPP equipment. This results in a fold increase of overall capital costs. If we consider that the amount of electricity produced in the stand-alone power supply system remains approximately unchanged, economic characteristics of the power system with wind generation deteriorate.



**Figure 2.** The block diagram of methodology of designing a rational option of the wind and diesel power supply system.

On the other hand, partial substitution of the diesel generation for wind generation saves expensive fuel and, reducing the operation time of diesel generators, increases their service life [9, 10]. Wind power equipment features longer life as compared to diesel generators, which also helps to improve the economic performance of the combined power facility.

Therefore, the decrease in profitability of norm coefficient  $P_n$  and operating costs of wind-diesel power contribute to the improvement of its economic performance. Obviously, economic feasibility of the construction of stand-alone wind and diesel power facility with separate operation modes of wind and diesel parts is achieved if the savings per annum in operating costs exceed the cost of compensation for the increased capital costs. These opportunities are more typical of stand-alone diesel power systems with high cost of electricity, determined primarily by the cost of fuel. Stand-alone systems with the main energy source – the continuously operating diesel power plant and the wind power plant, connected to it in parallel, according to the current wind energy potential, are less efficient. Typically, the wind power plant is connected to DPP through the grid tie inverter, which limits the maximum wind power at the level of 30-40% relative to the power of the diesel power system. The economic viability of these systems is only possible with very expensive diesel fuel.

### 3. Results and Discussion

The methodology of designing a rational, based on technical and economic parameters, option of the wind-diesel power system is shown as a block diagram in Figure 2. The input information for analyzing possible options of designing a stand-alone power supply system is wind power potential in the area of electrified facility and consumer's energy needs. High wind energy potential, characterized by the average annual wind speed of about 5 m/sec or more, allows choosing the structure of the wind-diesel power supply system with separately operating generating units.

At lower wind speeds, it is possible to design a more rational structure of combined power facility with the parallel operation of wind and diesel generating units, where diesel generation prevails.

In accordance with the structure of the chosen WDPP, wind power equipment is determined as follows: installed capacity of main generating units, an inverter type, availability and capacity of energy storage equipment. The DPP structure and composition are determined by the facility energy needs, recommendations to ensure energy-efficient modes of diesel generators and practically does not depend on the wind power plant. It should be noted that WDPP structure recommendations, depending on the average wind speed, can be adjusted according to the achieved economic project indicators.

Economic indicators of stand-alone wind and diesel power systems are determined by the overall capital investment and maintenance costs, and the volume of electricity produced and supplied to the consumer. Capital investment includes the equipment, design, construction and installation costs. We shall note that capital investment in the wind power plant sufficiently exceeds the costs of the diesel power plant construction.

Operating costs for the wind farm, due to the lack of fuel cost, operational staff and a long life of the power equipment is much less than those of DPP. An optimal option of wind-diesel power systems can be found by calculating the minimal prime cost of electricity produced. An optimization target function, in this case, should be expressed as  $E_{el} \leq \min$ . As the input information, we should take into account the stability of the wind power potential and facility power consumption. The installed capacity of DPP is unchangeable as it is determined by the maximum load power. The cost of diesel fuel remains unchanged or projected to change based on price fluctuations in recent years.

### 4. Conclusion

To sum up, optimization of the wind and diesel power plant can be reduced to a one-dimensional problem with the independent variable – WPP installed capacity.

The initial value of the WPP installed capacity shall be chosen based on the combined power plant structure and the interaction algorithm between wind and diesel parts. During separate operation of generating units, power ratio restrictions of DPP and WPP virtually do not exist. During combined operation of wind and diesel generators, DPP usually becomes the leading energy source. WPP available capacity, in this mode of operation, should not exceed 30-40% of the power generated by DPP.

Based on these recommendations, we shall choose the initial option of WPP installed capacity and calculate the cost of electricity. Further, according to the method of coordinate descent, we can change

the value of the optimization variable – the WPP installed capacity, taking into account available capacities of wind turbines with suitable characteristics and find a new value. Based on the difference sign, we shall adjust the direction to the minimum point and carry on calculating power equipment options for the combined power plant.

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