Development of isolated energy systems in Russia using renewable energy sources

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Abstract. The power system of Russian Federation is diversified regionally and consists of one Unified Power System and multiple off-grid power systems. Many parts of Russia are not connected to centralized power supply by virtue of their geographical position. There are more than five thousand autonomous energy sources in the off-grid territories, which are mainly represented by diesel power plants and gas turbines. These power plants use very expensive fossil fuel. It is proposed to use a large share of generation based on renewable energy sources (RES) for such systems. Taking into account a nonstationary character of power generation, presence of electricity storage devices, as well as stricter requirements of consumers to power quality and reliability of power supply, we can say that operating conditions of such systems and their control represent a difficult problem that needs to be studied. The tasks of substantiating the development of isolated power supply systems are considered. The analysis of the essence and level of study of task groups to substantiate the development of such systems in a hierarchical sequence is given. The problem of substantiating development is presented in the form of three successive stages: substantiating a rational configuration of the power supply system, comprehensive optimization of the structure and parameters of the power supply system taking into account various requirements and studying the operating conditions. In the paper, the specific features of microgrid operation in different seasons of a year and different time of a day are analyzed, a set of problems related to control of operation is formulated and specific features of their solution are discussed.

1. Introduction

Russia has many small isolated settlements mostly in the northern part of the country. They are supplied with electricity from diesel power plants using expensive fuel delivered at large distances. However, in many cases electricity can be supplied to consumers on the basis of RES. The studies show that in the majority of cases the use of RES is economically efficient. However, because of variable power generation from wind turbines and small hydropower plants, diesel power plants can serve as standby sources. Besides, for this purpose it is also advisable to consider energy storage systems. Electricity demand management and increase in the role of consumers in the process are topical as well.

The power supply system to be formed in such a way is a microgrid of a specific structure. Because of variability of power generation, availability of energy storage systems, electricity demand management and more stringent consumer requirements for power quality and power supply, reliability optimization of such a power supply system is a problem to be studied further.
This paper analyzes specific features of microgrid operation in different seasons of the year and at various periods of the day. Besides, a set of problems on optimal development and operation of the power generators for off-grid systems are formulated.

2. Off-grid power supply systems

About 60% of Russia’s territories, mostly in the North, are not connected to interconnected power systems due to their geographical location. This feature has a significant influence on the formation, development and operation of power supply systems for remote territories [1]:

• territories have a large area with a sufficiently low density of electrical loads,
• power in remote areas, mainly based on imported liquid fuel with a complex, time-consuming and seasonal delivery method;
• complex and mainly harsh climatic conditions of these regions also lead to a low level of reliability of energy supply to consumers.

A large number of scattered consumers which can be supplied with electricity only from local isolated power sources and the problems in the existing off-grid power system require urgent development and optimization of power generators for such consumers. An obvious way to enhance energy efficiency of such areas is maximal use of alternative and local energy resources. In this regard, the development of power systems for remote areas is an important task.

Currently, conventional fossil fuel power plants generate approximately 68% of all electricity in Russia. Nuclear power plants supply 11% and RES (wind, geothermal, hydro, and solar) produce the remaining 21% of which 99% is generated by large hydropower plants, 0.6% by biomass plants, 0.3% by small hydropower plants and 0.1% by wind and solar energy systems [2-4]. The intensive adoption of distributed generation facilities, however, continues, including those on the basis of RES [5-8].

Many studies are devoted to technical and economic assessment of power supply to off-grid systems [9-12]. The feasibility of connecting them to centralized power source or using local small power sources has been shown [13, 14]. Also the areas of efficient centralized and decentralized power supply are presented depending on electricity and diesel fuel cost.

The models created for isolated microgrid also include those intended to optimize the systems for control of distributed generation, including, in particular RES [15-19].

The above characteristics of remote territories in Russian Federation make the systems of power supply to these territories specific in terms of load flows and their control in different seasons of the year and different time of the day.

Given the scale of power supply systems, the entire set of requirements for their development and operation to ensure efficiency, reliability of power supply and power quality, and, as a result, the high complexity of modeling the entire complex necessary for a detailed account of factors and conditions, it is advisable to consider a hierarchical approach to solving problems of development justification for these systems, using the guidelines [20]. Based on the generalization of the existing experience in designing complex power supply systems, taking into account the ideology of the hierarchical approach, it is necessary to find the rational configuration of the power supply system, determined by the interposition and interconnection of elements in the power system.

3. Off-grid power systems expansion planning and control

Mathematical models and methods for complex optimization of the structure and parameters of power supply systems, including taking into account distributed generation, are discussed in [21-24].

Given the ideology of the hierarchical approach, the general problem of substantiating the development of active isolated systems must be represented in three successive stages:

1. Justification of a rational configuration of the power supply system, determined by the relative position and relationship of elements in the system.
2. Complex optimization of the structure and parameters of the power supply system, taking into account the requirements for its activity, reliability of power supply, power quality and economic efficiency of functioning and interaction with active consumers.

3. A study of the operating conditions of isolated system based on a detailed analysis of its normal, emergency, post-accident and other operating modes when fulfilling increased consumer requirements for the parameters of the modes, reliability of power supply and the quality of electricity in order to select management tools and activities to ensure operation of the power supply systems.

The problem of the complex development of isolated systems is very large, therefore, in this paper, we consider the mix of optimization of power generation for off-grid systems.

Approaches to formalizing the tasks of substantiating the rational configuration of the power supply system are presented in [24]. Developments in this direction are also analyzed in reviews [21, 25-28].

The problem of studying the operating conditions of an isolated power supply system can be considered as part of two interconnected groups of tasks:

• assessment of compliance with regulatory requirements for the parameters of the regime according to the conditions of reliability of power supply to consumers and the quality of electricity, by calculating the respective modes taking into account their economic efficiency under specified design conditions in accordance with applicable methodological and regulatory documents (state and industry standards, guidelines, etc.);

• in case of failure to comply with the specified regulatory requirements for the parameters of the regime, the justification of the necessary tools and measures for bringing the parameters of the regime to acceptable boundaries by reconfiguring the circuit of the power supply system and controlling its parameters in the above aspects; at the same time, the tasks of choosing the composition, parameters and locations of reconfiguration means and controlling circuit parameters (reclosers, switching devices, compensating devices for various purposes, etc.) are solved.

It should be emphasized the need to coordinate the various tasks of substantiating the means of reconfiguring the power supply system, their composition, parameters and arrangement, taking into account the real multi-purpose use of these resources. The criterion in this case may be the minimum cost for the entire set of possibilities.

4. Problems mix optimization of power generation for off-grid systems

According to the characteristic of off-grid power systems in Russia optimization of their expansion requires consideration of generation units that use fuel and RES for production of electricity and heat [29, 30]. Due to variability of consumer load curves and uneven power generation from RES, energy storage systems are taken into account. The representation of off-grid power system relies on balances between generation and load that are specified with weekly discretization.

Thus, the optimization problem of the off-grid power system expansion is represented as the following mixed-integer linear programming problem for each time instant of the day, taking into account the level of discretization of power generation and consumption curves:

\[
\min \sum_{i=1}^{n} C_i \left( u_i P_{gi} \right) \tag{1}
\]

subject to constraints

\[
\sum_{i=1}^{n} P_{gi} = P_{e_{gi}} \tag{2}
\]

\[
u_i P_{gi}^\text{min} \leq P_{gi} \leq u_i P_{gi}^\text{max} \tag{3}
\]

\[
i = 1, n \tag{4}
\]

where \( u \) is a binary variable that takes a value of 0 or 1 to take into account the presence (1) or absence (0) of power generation from the unit of a certain type \( i \); \( i \) is the number of time instants during the discretization period of power generation and consumption curves; \( K \) is the number of intervals in
which the cost characteristic of power generation by the units of power plants is linearized; $P_{e,\text{r}}$ is the total load of a system; $P_{e,i}$ is power generated by the unit of type $i$.

By solving the formulated problem we:

1. Minimize the costs of power electricity production during the considered day by following procedure:
   - for a given weekly load curve,
   - for the given wind and insolation conditions,
   - calculate the wind and PV load using generic models of wind and PV generators,
   - substrates the energy generated by renewable from the weekly load profile,
   - use the traditional generation to fully balance the needed power (energy).

2. If the generation form RES will be higher for some period of time then the given weekly load profiles an electric energy storage system can be used to save the produced green energy. This saved energy can be in-fed into the system replacing the traditional generation and in this case save the fuel resources.

5. Case study for off-grid system

As a case study, we consider a test off-grid power system, which is located in the northern part of Russia. The test system consists of:

- Load - 25 MW as per the weekly load curve.
- Wind generation - 10 MW
- PV generation – 2.5 MW.
- CHP generation - 25 MW.

Four basic scenarios have been considered:

A. Basic mix of generation given below.
B. High share of PV generation: PV- 5 MW.
C. High share of wind generation: Wind -25 MW.
D. High share of total RES: PV-5MW, Wind -25 MW

Using wind and insolation profiles, the wind and PV generation can be accounted for, using the generic models of wind and PV systems.

Figures 1-4 shows the share of the participation of different generation in the covering of the load profile. In general the investigation results strongly depend on the local wind and solar radiation conditions.

The input data for this simulation should include weather data, so that it reflects the local conditions well. Also, the load curve should correspond as closely as possible with the local conditions.

It is obvious that a further increase in PV output will not reduce the cost of fuel for this test off-grid system (Figures 1-4). The fact is that the contribution of PV-generation is very small. This is due to the climatic conditions and the length of daylight for the considered northern territories of Russia. For the final decision, the limiting factors are the cost and climatic conditions.

To decide on the structure of generating sources, the criterion of the minimum cost of fuel for generators is not enough in an off-grid power system.

To optimize the generation structure, a multicriteria problem has been solved. The following optimized parameters were investigated:

- Cost of fuel;
- Emissions CO$_2$ and NO$_x$;
- Capital costs for the construction of generators.

The emission is calculated taking into account the equivalent emission for different technologies [31].
The necessary generation mix for each hour was found by using the mentioned mixed-integer linear programming solution. The priority of renewable introduction has been set.

The research results for the four scenarios above are presented in Table 1. All data are given in relative units. For the baseline, the maximum values are taken for each indicator.

Table 1. Comparative analysis of different scenarios of mixed generations for considered off-grid power system

| Scenario | Fuel cost | Emission | Construction | Energy per week |
|----------|-----------|----------|--------------|----------------|
|          |           | CO₂      | NOₓ          | CHP, MWh       | RES, MWh       |
| A        | 1         | 1        | 1            | 0.52           | 1221           | 635           |
| B        | 0.79      | 0.96     | 0.96         | 0.56           | 1168           | 683           |
| C        | 0.62      | 0.76     | 0.76         | 0.95           | 915            | 1214          |
| D        | 0.60      | 0.74     | 0.74         | 1              | 868            | 1272          |

The CO₂ and NOₓ emissions are approximately the same, so it is enough to use just one of these indexes.

The graphic interpretation of this comparative analysis in the form of an optimization diagram is shown in the figure 5. The best solution in this case is the scenario with the smallest area.

From the analysis of table 3 and the graphical interpretation of the optimization results (Figure 5) it can be seen that scenario A is the best option in this case, despite the high fuel costs. At the same time, it should be noted that doubling generation from renewable energy sources reduces emissions by only 25%.
Figure 5. Graphical interpretation of optimization results for different scenarios

6. Conclusion
An analysis shows that the least definite idea of the essence of tasks is characteristic of the stage of studying the conditions of functioning of active power supply systems in order to select the necessary measures and controls. The proposals formulated in the article systematize the composition and essence of the tasks of this stage and provide information on the directions for their formalization. The paper proposes a technique for finding the optimal combination of generation sources for off-grid power systems, taking into account their specific features. At the next stage of studying the problem, it is necessary to develop models and methods for solving individual problems and coordinate the solutions.

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