Designing the power supply system of the region with the integration of hydrogen energy facilities

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Abstract:
The paper considers the methodology of designing a distribution network by the example of the Penza region in Russia. We performed a simulation of operating modes and optimization of the distribution network topology. The power balance in the power system was performed in autonomous mode. Recommendations were given on the placement of renewable energy sources (RES) on the ground and the selection of their capacity. The total capacity of renewable energy generation facilities exceeds the design load 3 times. A balancing load is included in the power system to increase the efficiency of renewable energy generation facilities. Electrolysis hydrogen stations consume excess electricity generation during the periods of favourable weather conditions. Hydrogen is stored in the warehouses and can be used at the thermal power plants during periods when weather conditions are unfavourable and the generation of renewable energy sources is insufficient to supply the region.

1. Introduction
At the turn of the XXI century, civilization faced a number of problems related to the growth of energy consumption, the increase in the cost of line and reduction of fuel production, environmental pollution. The main means of solving the problem of greenhouse gas emissions is avoiding traditional hydrocarbon energy and the introduction of renewable energy sources (RES) [1]. Renewable energy sources (RES) include wind energy, geothermal and solar energy and they confidently occupy a leading position in terms of the rate of implementation in the energy sector.

The global renewable energy market is growing quickly, the installed capacity in wind power station (WPS) in 2008 increased by 28.8 %, by 50% - in solar energy station (SES).

The wind power generation is 40% of total electricity in Denmark. The wind and solar energy amounted to one-third of generating capacity in 2014 in Spain [1]. Achieving a high share of wind and solar energy in the balance of energy systems is technically feasible, but implementation of the RES expansion is hindered by economic factors.

The design of district distribution electric networks is an optimization problem with boundary conditions. Owing to insufficient information about the modes of operation of consumers and forecasts of the development of the region, there is no single solution task. In practice, several variants of the network topology are being worked out and the choice of a working project is made based on the method of expert estimations.
A mathematical model was developed to study the modes of operation of the power supply system using distributed generation from renewable energy sources (RES). This mathematical model is based on the characteristics of the modern wind and solar power. The model is based on the regional power supply system in the Volga region [9]. The generation of electric and thermal energy is carried out at the thermal stations. Partially, the needs of the region are covered by transit through the main 500 kV transmission lines.

The power supply system is built on the principle of combining local networks [2]. The territory of the region is divided into 7 production districts.

Table 1 presents the characteristics of consumers. The regional center has the main part of the load. A railway passes through the territory of the Penza region and three traction substations provide power.

Table 1. Characteristics of the electrical loads in the region

| No. | Appellation       | Installed capacity, MW | Rated power, MW | Utilization rate | Coordinates X, km | Coordinates Y, km |
|-----|-------------------|------------------------|----------------|------------------|------------------|------------------|
| 1   | Regional center   | 940                    | 420            | 0.45             | 124              | 56               |
| 2   | District center 1 | 32                     | 18             | 0.56             | 23               | 25               |
| 3   | District center 2 | 32                     | 16             | 0.50             | 192              | 74               |
| 4   | District center 3 | 40                     | 24             | 0.60             | 154              | 18               |
| 5   | District center 4 | 24                     | 15             | 0.63             | 26               | 72               |
| 6   | District center 5 | 24                     | 14             | 0.58             | 86               | 14               |
| 7   | District center 6 | 16                     | 10             | 0.63             | 134              | 85               |
| 8   | District center 7 | 32                     | 21             | 0.66             | 66               | 63               |
| 9   | Industrial complex | 70                   | 29             | 0.41             | 27               | 32               |
| 10  | Traction 1        | 32                     | 14             | 0.75             | 74               | 85               |
| 11  | Traction 2        | 40                     | 14             | 0.60             | 140              | 52               |
| 12  | Traction 3        | 40                     | 14             | 0.60             | 176              | 16               |
|     | Total districts   | 270                    | 147            |                  |                  |                  |
|     | Total region      | 1322                   | 609            |                  |                  |                  |

Regional networks operate under 110 and 220 kV voltage. The maximum length of power lines from the power center to the node transformer substations (TS) is 200 km. District distribution networks operate with a nominal voltage of 35 and 10 kV. The transmit electricity distance is 50 km. The estimated load capacity for the region is 609 MW, of which the regional center consumes 420 MW and load capacity of districts is 147 MW. The transit losses are 42 MW.

2. Materials and methods

The mathematical apparatus for searching for the local extremum of the objective function is used in resolving the design problems of developing the topology of distribution networks and determining the coordinates of the power centers and local generation facilities. The given operating costs, the amount of electricity losses for transit, the length and cost of the power transmission lines are used as an objective function [3].

The methodology of designing and building networks is based on minimizing the loss of electricity for transit from the power center to consumers. When transmitting the same power, the amount of loss will be proportional to the length of the line. So, it is necessary to choose a scheme with the shortest length and technological possibility of laying power transmission lines. The obtained coordinates of the centers of electrical loads (CEL) and the center of electrical generation (CEG) are optimal, they provide minimal losses during transit [2, 8].

But during the construction of transformer substations (TS) and ballast load, many other factors...
have to be taken into account - the terrain, the presence of reservoirs, the nature of the soil, the presence of transport routes, residential buildings, industrial facilities, and protected areas. In any case, energy facilities tend to be placed as close as possible to the calculated coordinates [3].

The district center 3 and the industrial complex have their own generation at low-power thermal power plants. The characteristics of loads, objects of centralized and distributed generation of renewable energy sources are presented in Table 2.

**Table 2.** Characteristics of the electric power generation facilities

| No. | Appellation      | Installed capacity, MW | Rated power, MW | Utilization rate | Coordina tes X, km | Coordina tes Y, km | Area, ha |
|-----|------------------|------------------------|----------------|------------------|--------------------|--------------------|---------|
| 21  | Thermal station -1 | 400                    | 320            | 0.80             | 118                | 64                 |         |
| 22  | Thermal station -2 | 250                    | 180            | 0.72             | 126                | 58                 |         |
| 23  | TS Combine        | 63                     | 48             | 0.76             | 36                 | 34                 |         |
| 24  | Thermal station -3 | 80                     | 50             | 0.63             | 147                | 18                 |         |
|     | Total TS         | 793                    | 598            |                  |                    |                    |         |
| 31  | SES-1            | 45                     | 14             | 0.31             | 12                 | 56                 | 23      |
| 32  | SES -2           | 45                     | 14             | 0.31             | 54                 | 12                 | 23      |
| 33  | SES -3           | 45                     | 14             | 0.31             | 172                | 92                 | 23      |
| 34  | SES -4           | 45                     | 14             | 0.31             | 190                | 34                 | 23      |
| 35  | SES -5           | 25                     | 7              | 0.28             | 54                 | 66                 | 13      |
| 36  | SES -6           | 25                     | 7              | 0.28             | 116                | 88                 | 13      |
|     | Total SES        | 230                    | 70             |                  |                    |                    |         |
| 41  | WES-1            | 66                     | 16             | 0.24             | 43                 | 48                 | 232     |
| 42  | WES -2           | 60                     | 15             | 0.25             | 8                  | 77                 | 220     |
| 43  | WES -3           | 58                     | 19             | 0.33             | 72                 | 40                 | 196     |
| 44  | WES -4           | 56                     | 18             | 0.32             | 112                | 16                 | 182     |
|     | Total WES        | 240                    | 68             |                  |                    |                    |         |
|     | Total            | 1063                   | 736            |                  |                    |                    |         |

The classical algorithm for designing networks in the conditions of using distributed generation facilities gives significant errors and cannot guarantee an optimal structure for several reasons.

1. The power supply of the district is carried out from an electric station, a power center or transformer power plants. They have a small area and are indicated by a dot on the plan. The use of wind power plants (WES) and solar power plants (SES) requires significant areas; the size of sites with installed equipment reaches several tens of kilometers. On the plan, they are indicated by zones.

2. In the conditions of centralized power supply, power supply centers are built near the maximum power consumption. These are large cities, industrial centers, transport hubs. The construction of renewable energy facilities in these places is impossible. Generation objects are taken out of cities, suburban areas and placed on a free territory. The selection of zones is carried out near the existing routes of power lines.

3. The center of electrical loads is found to optimize the locations of power centers. For renewable energy facilities, an electric generation center is located in a similar way, in which a transformer substation is installed to connect to the district networks. The solar energy capacity will change throughout the day, so the formulas use unspecified, but calculated capacities [1]. The estimated capacity of the wind power plants (WES) is less than the installed one and will change greatly during the year.
4. Thermal power plants operate in a controlled way. Depending on the total load in the network, the dispatcher issues a command to generate the specified power. The maximum capacity of renewable energy facilities for a given area highly depends on weather and climatic conditions. To ensure a balance in the energy system, the installed capacity of RES is several times higher than the calculated load.

5. Under favourable weather conditions, the maximum generation capacity can be many times higher than the needs of the district. To achieve a balance in the energy system, it is necessary to limit the power of renewable energy sources, or to issue surplus to the network or connect a balancing load for this time. This requires increased line capacity.

6. The maximum transit capacity of district networks will be determined not by the maximum load, but by the maximum possible output of power [4]. In this case, the topological schemes and the cost of power lines will be greatly overestimated. But the networks will be operated with the maximum load for a limited number of days per year.

7. Under unfavourable weather conditions, the power of RES generation can dramatically decrease, and at night and in the absence of wind it can completely disappear. So, for reliable power supply to consumers in the district, it is necessary to include thermal power stations and power supply centers on the branches of main transmission lines in the power system.

For partial replacement of generation at thermal power plants in the region, it is planned to build 6 SES with an installed capacity of 224 MW and 4 wind farms with a capacity of 240 MW [4].

The main generating unit of the wind farms is a GW 93/1500 wind turbine of the company Goldwind (China) with a nominal capacity of 1.5 MW [5]. The starting speed is 2.5 m/s, the nominal speed is 9.3 m/s, the maximum permissible speed is 22 m/s. The diameter of the blades is 93 m and the height of the rotor axis above the ground is 60 m [2]. The choice of this brand of wind turbine is due to the low starting speed, which ensures its maximum efficiency. The average annual wind speed is 5 m/s in the conditions of the Volga region.

The standard equipment of the company "Hevel" was selected for the SES. The SES consists of clusters, and each cluster consists of modules with a capacity of 0.38 kW [6]. Each cluster with a total capacity of 5 MW has 14 thousand modules [3], occupies an area of 2.5 hectares. SES 1-4 include 9, and SES 5 and 6 include five typical clusters. With the integration of SES with pastures, the area will increase 6 times.

Figure 1 shows a cartogram of loads and a plan for placing objects on the ground.
RES facilities are recommended to build in rural areas and in the suburban area. In urban areas the use of RES is impossible for the following reasons:

1. It is impossible to obtain the significant required generation capacity with the existing RES equipment.
2. It is dependence on weather conditions. The inability to ensure a given level of reliability of power supply.
3. There are restrictions on the use of such vibration and noise of the WES facilities.
4. Heat energy needs for heating and technological purposes.
5. It is lack of free space for the placement of SES and WES facilities.
6. It is increased danger of renewable energy facilities for people and animals.

Electricity supply to all consumers of the regional center, suburbs and traction substations of the railway is carried out from the thermal station (TS)-1 and thermal station (TS)-2. They are located within the city. In district center 3 there is thermal station (TS)-3, which provides power supply to the district center and the railway. The area of the figures is proportional to the calculated power. A thermal power plant operates at the site of the industrial plant, which provides for the needs of the plant and the nearest settlements.

Under favourable weather conditions, the generation capacity of RES is sufficient to supply all consumers in the adjacent territory. The excess capacity of renewable energy sources is supplied to the distributed network. In this case, the capacity of thermal power plant (TPP) and thermal station (TS)-3 can be reduced to the level of the required thermal power. This will reduce the amount of fuel burned and reduce emissions of harmful substances, including carbon dioxide into the atmosphere.

3. Results and Discussion
Free plots of land, which are not occupied in agriculture, were taken into account when choosing sites for the construction of WES and SES facilities. Part of the territory is occupied by forests; part of the territory in the floodplain of the river has swampy soils. The suburban area of the regional center has very dense low-rise buildings and industrial zones. Wind farms are located in the river valley, where wind speeds are slightly higher than the average for the region [4].

In view of the considerable length of the districts, we divide the territory of the region into several zones. There will be RES facilities. If the number of zones is small, it will be a large distance between objects. Transmission of electricity by district networks at low voltage leads to an increase in losses [2, 3]. If the number of zones is increased, many zones will have a design capacity that is less than nominal. Operation of this equipment in this mode is also ineffective.

Figure 2 shows a nomogram of the dispersion of the scattering of objects relative to CEL and CEG for a different number of zones. 5 zones were adopted for implementation and a further increase in their number does not give the expected effect.
Figure 2. Influence of the number of zones on the dispersion of the CEL and CEG scattering of the region.

Table 3 shows the results of calculations of the most probable modes of operation of the power supply system of the districts and the distribution of objects by zones. For the mode of generating the average RES capacity, it is possible to meet the needs of all districts, except for the first. The missing power of 5 MW is compensated by transit. During peak hours, the transit power increases in all regions, except for the second.

Table 3. Grouping of RES facilities by zones

| No. | Appellation                      | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 | Total |
|-----|---------------------------------|--------|--------|--------|--------|--------|-------|
|     | Generation facilities:          |        |        |        |        |        |       |
|     | Thermal power plants            | 24,    |        |        | 31,    | 42,    | 464   |
|     | SES facilities                  | 33,    | 34     | 32,    |        | 35     | 423   |
|     | WES facilities                  | 44     | 41     | 42     | 43     |        |       |
| 1   | Peak power, MW                  | 67     | 125    | 101    | 121    | 193    | 464   |
| 2   | Design power, MW                | 21     | 64     | 32     | 67     | 52     | 236   |
| 3   | Loads according to the list      | 3, 7   | 4      | 6      | 2, 9   | 5, 8   |       |
| 4   | Load power                      | 26     | 24     | 14     | 47     | 36     | 147   |
| 5   | Transit power, MW               | -5     | 24     | 3      |        | 22     |       |
| 6   | Electrolysis power, MW          |        | 14     | 18     | 16     | 67     |       |
| 7   | Maximum power, MW               | 41     | 45     | 87     | 41     | 157    | 371   |
| 8   | Output per month max., MW-h     | 12300  | 13500  | 2610   | 12300  | 47100  | 87810 |
| 9   | Average monthly output, MW-h    | 4200   | 5400   | 4800   |        | 14400  |       |
| 10  | Hydrogen output per month max., t| 246    | 270    | 522    | 246    | 942    | 2226  |
| 11  | Output of hydrogen per month average, t| 84 | 108 | 96 | 288 |
| 12  | Number of modules of the electrolysis hydrogen station | 20 | 50 | 66 | 20 | 62 | 218 |

For average statistical meteorological conditions, the power of RES is sufficient to supply power to all regions. 45 MW of power will be transmitted through the district networks to compensate for transit losses and uneven generation. It is possible to issue 308 MW of excess power in the network.
with the maximum generation in the daytime and at night the transit will be 88 MW. With an estimated load capacity of 147 MW, the networks should provide transmission of 30% in normal mode and 200% of the power in peak mode.

A ballast load is built into the renewable energy facilities to increase the efficiency of using renewable energy generation facilities in the maximum power mode. It is proposed to use electrolysis hydrogen stations (EHS) as a ballast load in the power system. The equipment of the Belgian company "Stuart Energy System" was accepted as a working version of the project [7]. The capacity of the station module is 9.6 kg of hydrogen per hour. Consumed electric power is 500 kW. It is necessary to solve the problem of choosing the number of electrolysis hydrogen stations modules and their location for each district.

The equipment consumes 50 MWh of electricity to generate 1 ton of hydrogen by electrolysis of water [4]. The production of hydrogen by one electrolysis hydrogen stations module will be 100 kg per day and 3 tons per month. At the same time, the energy consumption per month is 150 MWh. Analysis of the table shows that the equipment will be constantly loaded in zones 2, 3 and 5. The equipment will be idle more in zones 1 and 4. So, the number of modules there will be reduced.

Taking into account that the maximum capacity of SES observed in summer during a time of 6-8 hours, and the rest of the time is small, the actual production of hydrogen will average 144 tons. In this case, some of the EHS modules will be idle. If the generation capacity of renewable energy facilities is low, all or part of the EHS modules will be turned off due to a lack of electricity [9]. Downtime for the Volga region will be approximately 120 days a year.

In the peak mode, on the contrary, the generation power will exceed the maximum power of all modules. The production of hydrogen will reach 650 tons per month. In this mode, all modules will work approximately 30 days a year. If there are consumers, excess electric energy can be transferred to the district networks. So, the design of district networks is carried out according to the coordinates of the CEL and CEG. The transmission capacity of the transmission line will be equal to the peak power of renewable energy sources supplied to the power system. Otherwise, the capacity of renewable energy generation will have to be limited; this has a negative impact on economic indicators.

4. Conclusion

As a result of the conducted research, a power supply system was designed with distributed generation based on renewable energy sources. We performed the simulation of the operating modes of generators and power lines under various climatic conditions. We determined the capacity and placement zones of SES and WES facilities. They meet the needs of the districts in electric energy. The topology of the district network and the transmission capacity of the transmission line are determined by the ratio between the design power of the loads, the capacities of centralized and distributed generation.

A feature of the design of power transmission lines is the unstable generation of renewable energy sources and the possibility of electricity transit in two directions. In this case, the transmission capacity of the transmission line is determined by the power of excess generation. A ballast load is included in the power system to increase the efficiency of renewable energy sources during periods of maximum power. Electrolysis hydrogen stations are used as a ballast load. The choice of capacity, the number of installations and their location are also an optimization task. The production of hydrogen, its subsequent storage and use as a fuel in thermal power plants will preserve the power of distributed generation in adverse weather conditions.

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