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The Complex Optimization of the Solar Power Plant

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ABSTRACT
The structure of the solar power plant is given. The issues of optimization and location of objects on the ground are considered. An assessment of electricity losses on internal lines was estimated.

***Keywords**: Solar power plant, Inverter, Step-up transformer, Electric generation center, Losses of electrical energy.*

1. AN ANALYSIS OF THE ISSUE

There are trends in the transition from carbon-containing fuels to renewable energy sources (RES) in the global energy sector [1]. The government of the Russian Federation in 2021 published a number of orders suggesting the transition to the “Green Economy”. This is a set of measures aimed at reducing greenhouse gas emissions, subsequent waste recycling and the transition to renewable energy sources. The lack of experience in practical use and the imperfection of legislation in the field of renewable energy led to mistakes of designers and ineffective use of generation facilities based on renewable energy sources. The use of solar panels for electric power generation requires fundamentally different approaches in the design of solar power plants. [2].

In world practice, there is a sufficient experience in the use of renewable energy sources both in large solar power plants (SPP) and in distributed generation (DG). DG in a local area with a large number of consumers and RES facilities provides opportunities to use surplus generated electricity for distribution to energy-deficient areas of the country.

The installation of group converter substations is proposed for the efficient use of DG capacities and the power supply of consumers of scarce areas. Power flows within such areas will be minimal. The simultaneous generation of SPP and power consumption will allow to align daily load schedules and increase the efficiency of renewable energy use. The installation of one high-power inverter converter for a group of renewable energy facilities will reduce the cost of the solar power plant and the cost of electricity.

2. RESEARCH

Wind and solar power plants belong to DG. The unit power is small, so a distinctive feature of RES is the location of generating equipment in a significant area. Grouping of solar panels and sectioning of sources at different voltage levels are used to generate high power. Figure 1 shows the structural diagram of the solar power plant.

The scheme of the solar power system is built according to the hierarchical principle with the direction of power transit from the bottom to the top. Electricity is generated by solar panels with a nominal voltage of 40 V [3]. Transit through the territory of the solar power station is conducted on power lines (transmission lines). Direct current makes it easier to connect a large number of sources to the common bus of the converter station. Solar panels are grouped into modules. Solar panels are connected in series and in parallel inside the module, thus the voltage at the pins of the line and the output current increase. When using a large number of renewable energy facilities at large solar power plants, solar panels are grouped into modules and modules into clusters. Each cluster has several inverters and a transformer substation (TS). To reduce the number of inverters, their power is increased to values limited by the maximum currents of thyristor switches.

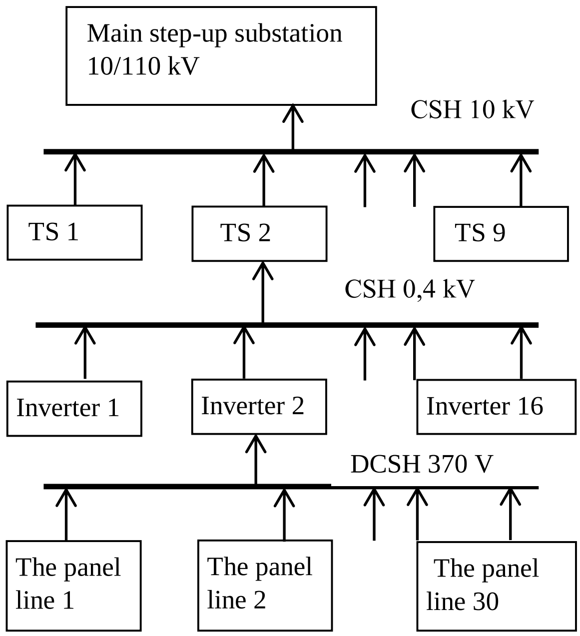

Figure 1 Structural diagram of the SPP.

The amplitude of the phase voltage is 310 V in 0.4 kV distribution networks. Conversion of direct current to alternating current is performed by inverters with six thyristor switches [4]. A throttle is sequentially connected to the circuit of each phase to obtain a sinusoidal form of voltage. Into account the voltage losses at the throttle, it is required to obtain a voltage at the output of the modules and DC buses equal to about 360 V.

The module includes 270 panels. The module in DC mode produces a peak power of 108 kW. When working together with an inverter, the current of one module is distributed into three phases and will be less than the current in the transmission line. As a result, the amplitude of the current in one wire is 150 A, the electric power drops to about 73.6 kW at the output of the converter. These data relate to peak loads, which are observed no more than 1–2 hours per day. The rest of the daylight hours the power of the sun is less and the electrical power of the module decreases.

As the experience is gained in design and practical application, the main problems and solutions are identified. Often the adopted design solutions do not correspond to the technical characteristics of the modern element base and need to be improved [5]. Optimization of the solar power plant structure includes the following stages:

1. Designing of the main scheme of the SPP.

2. Designing of TS and main step-up substation.

3. Designing of modules and clusters.

4. Location of TS and main step-down substation on the ground.

The selection of the voltage is performed according to traditional methods at which the power output is carried out. The nominal voltage depends on the transit power and the length of the power lines. As a rule, the output of power up to 1 MW is carried out at a voltage of 10 kV over a distance of several kilometres. [4]. Transit power up to 10 MW is carried out at a voltage of 35 kV, and the transmission of higher power at a distance of up to 100 km requires a voltage of 110 kV.

The main scheme of the SPP is determined by the installed power. The number of conversion stages and TS depends on the peak power of generation and the voltage of the district networks to which the SPP is connected. An inverter is required to produce alternating current. An increasing TS of 0.4/10 kV is required to supply local consumers at a voltage of 10 kV.

Power delivery in the trunk lines is carried out through the main step-up substation, which are connected to power lines with a voltage of 110 kV. The power supply of the main panel of SPP is performed by direct current. An alternating current with a nominal voltage of 0.4 kV is required to supply auxiliary electric receivers. Some of the SPP receivers can operate at a generator voltage of direct current 360 V.

It is necessary to increase the transit voltage to reduce the current in the transmission line. A single-transformer TS is installed in each cluster for this purpose. The use of 0.4\10 kV serial transformers allows you to apply standard designs, solve problems with the supply of components at the construction stage and problems of spare parts during operation. The capacity of the SPP depends on the area, which it occupies. For example, for modern solar panels “Silasolar-400vt,” the peak specific power reaches 200 W/m2 [3]. For middle latitudes compared to the south of our country, solar activity decreases and the peak power decreases to 100 W/m2. The average specific power in the central part of Russia does not exceed 60 W/m2 taking into account the structural installation of panels, transport corridors and the placement of facilities on the territory of the solar power plant.

An increase of the capacity of the solar power plant requires to increase the area and the distances from the converter substations to the transformer substations also increase. This leads to an increase in the total length of indoor transmission lines. An increase in the active resistance of the transmission line leads to an increase of electric power losses for its transmission inside the SPP. The power of thermal losses in the transmission line depends on the line resistance and the current squared.

The cost of electricity generated by SPP does not include fuel costs. The price of electricity losses for transit will be significantly lower than the cost of cable products. You can use cables with an oversized section of current conductors to reduce the active resistance of power lines. This dramatically increases their cost and leads to an increase of the capital costs. On the contrary, a decrease in the current in the power transmission line, for example, by a factor of 2 leads to a decrease in the losses by a factor of 4. This way of reducing electricity losses for transit is economically justified.

The design of the SPP «from scratch» allows you to apply typical projects, maintain the topology, select rectangular sections, and place objects in the geometric centre of the areas. This approach minimizes the length of transmission lines and reduces the consumption of cable products. In turn, the total active resistance of the lines and the loss of electricity for transit is reduced.

In classical generation, the unit power of the units is concentrated in the local volume and it is considered a point. Renewable energy sources are used according to DG technology and the capacity is distributed over the territory. The use of solar panels of the same capacity, the same manufacturer or compatible in technical characteristics allows you to deliver the same power from 1 m2 of surface.

However, such favourable design conditions are almost never realized in practice. Standard projects of power plants based on RES have to be adapted to local conditions. It is necessary to take into account the terrain, riverbeds, flooding zone, forests, swampy soils, steep slopes of mountains. Renewable energy facilities often combine with agricultural land and solar power plants place on pastures [5].

SPP should be located as close as possible to consumers of electricity – large cities and industrial enterprises. But there are no free land plots inside the cities. Placement of solar panels on the walls and roofs of buildings does not give the required power and solves the problem of power supply only for low-power receivers. In the industrial area there are often emissions of dust, soot, moisture, aggressive substances, which negatively affect the performance of the SPP.

3. SIMULATION RESUITS

The task of calculating electricity losses for transit on internal lines, the consumption of electricity for their own needs, the optimization of the structure of the SPP becomes invariant. The authors propose to introduce the concept of the centre of electric generation (CEG) to determine the optimal location of the main step-up substation, inverter and transformer substations.

The CEG is the point on the plan of the power plant where the total capacity of all sources located in the allocated area is concentrated. The coordinates of the CEG at a given time of day are found by the formula:

$$X_C = \frac{\sum P_j \cdot t_j \cdot X_j}{\sum P_j \cdot t_j} \quad (1)$$

where P_j – average power of generation of the j-th source at a given time, kW; t_j – duration of the time interval, h; X_j – coordinates of the j-th source, m.

The CEG is not constant and it can also shift over time of day or time of year. Changes in the power output of different modules, their operating time, emergency shutdowns of modules and power lines lead to drift of the DER within the dispersion ellipse. Here you can see an analogy with the centre of electrical loads (CEL), which is used in the design of power supply systems. The installation of inverters and step-up transformers in the CEG will reduce the length of transmission lines and minimize losses during power transmission inside the SPP.

Analysis of the methods for determining the CEL allows us to conclude that they can be used to determine the CEG. It is enough to replace a group of low-power sources – solar panels, distributed over the area with points of single generation. When we consider a specific SPP, in the most cases single generation elements of one particular type are used [5]. This means that the same weight coefficients of the single generation will be used in determining the CEG.

An even more complex picture appears when solar panels with different technical characteristics are used in neighbouring areas. The construction of large objects is divided into stages and at each stage the contractors and equipment suppliers may change. During the process of ongoing repair or reconstruction of objects panels are also replaced with more modern, with improved characteristics.

In this way, the definition of the CEG for the SPP is reduced to the solution of the classical transport problem. This technique can be successfully applied to find the location of the TS on individual areas and for the location of the main step-up substation on the territory of the solar power plant. Today the most widespread method for determining the CEL is the method described in [6].

Recently, the method of distributed specific capacities has become widespread in the practice of designing power supply systems of districts. This method is based on the representation of distributed loads by figures of rotation of a certain function around an axis passing through the point with the coordinates of a particular equivalent load. The change of the parameters of specific power distribution at the considered site allows to determine both local and global CEL [7].

The basic function has the form:

$$p_{y\partial}(x,y) = P_i \frac{1}{2\pi\gamma^2} e^{-\frac{(x-a)^2+(y-b)^2}{2\gamma^2}} \quad (2)$$

where $p_{y\partial}(x,y)$ – specific power at each point of the considered area with load distribution P_i, kW/m^2; P_i – active power of the load or unit of the single generation; a, b – coordinates of the object of the single generation (axis of rotation), m; γ – characteristic of the distribution of specific capacities on the considered area, m.

The appearance of the figure of rotation is shown in Figure 2. The volume of the figure under the curved surface is equal to the total installed power of all sources installed on the territory of the SPP [7]. The volume of the figure with the unit area of the base is equal to the total power of generation on the area in the given coordinates.

The characteristic of the distribution γ – it is the distance from the axis of rotation to the surface of the figure, determined at the point of the inflection of the surface. It is the larger the area, the more power and volume of the figure. The characteristic of the distribution allows you to select the unit capacities of power equipment – transformers, located in the TS.

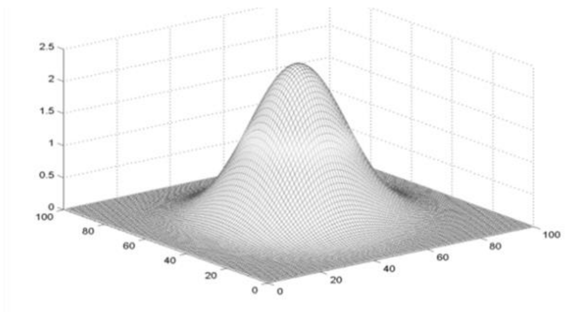

Figure 2 The dependence of the specific power of loads on the coordinates.

We consider a general case where unit powers of distributed generation objects are not equal to each other and they have an uneven distribution over the territory. Let's simulate the SPP of 9 clusters located in an area of 1000x1000 m in arbitrarily selected climatic conditions. For the daily peak the distribution of the specific power over the territory at γ = 6 m will take the form of Figure 3.

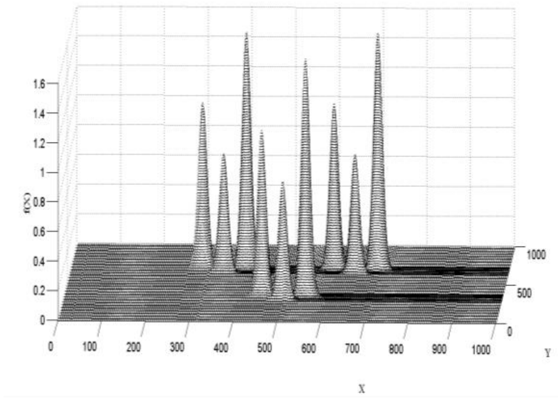

Figure 3 The distribution of the specific generation capacity over the territory of the power plant at γ=6

In the graph of Figure 3, the coordinates of the peaks coincide with the CEG of the clusters and the height of the peaks depends on the total power of the modules combined in the cluster. You can equalize their powers by changing the boundaries of the cluster. In this case, the coordinates of the peaks will also shift. This optimal connection of the modules allows to unify the power equipment.

The use of the same transformers, inverters, switches facilitates the solution of various problems during the operation. If it is not possible to select transformers for the power values of the clusters, you can change the parameter γ and get another distribution surface with a lower peak height and a lower power value of the converter substations, but a larger number of them.

An increase of the distribution characteristic γ up to 70 m gives a new distribution of the specific power, the graph is shown in Figure 4. The coordinates of the new peaks can be considered as local centres where inverter converters and step-up transformers of higher power can be installed. A further increase in the value of the characteristic γ will give the distribution of the specific power in the form of a single-vertex surface (Figure 2). The vertex coordinates and will be the coordinates of the CEG SPP and the main step-up substation 10/110 kV should be located as close to the CEG.

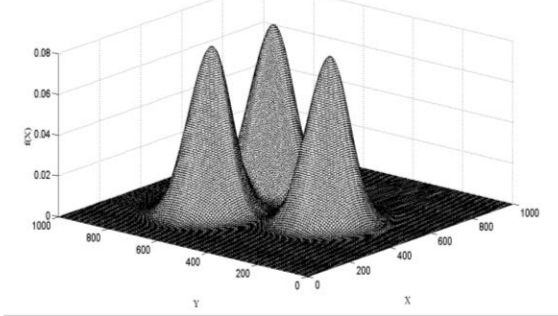

Figure 4 The graph of the specific power of the power plant generation at γ = 70.

If the SPP has a large area and significant capacity, the distribution in Fig. 3 and the coordinates of the CEG vertices show that the power of the clusters is too high. The values of currents and distances from the extreme modules to the TS will be large and the length of the transmission line will increase. The model calculations show that the transition from the distribution of Fig. 3 to the graph in Figure 4 will lead to an increase on the internal line currents and a sharp increase of the thermal losses.

For the SPP with a capacity of more than 100 the distribution in Figure 4 gives reason to conclude that the optimal solution for such SPPs would be the introduction of three main step-up substations in the structure. The coordinates of the placement of the main step-up substations coincide with the tops of the peaks in Figure 4. The output of the electrical power to the main and regional distribution electric networks will be carried out through spikes from the main 110 kV transmission lines to the 10 \ 110 kV main step-up substations.

The main step-up substation in the standard SPP projects, as a rule, is located on the border of the SPP land plot. We can conclude that its location is not optimal. The relocation of the substation to the CEG (Figure 2) due to the decrease of the total length of 0.4 kV power lines for the considered example will reduce the losses for the transmission of energy through the SPP territory by 16 %.

The application of both methods for the global CEG gives the same results. However, only the second method allows you to define the local CEG without performing additional calculations for dividing objects of the single generation into groups. [7].

The value of the losses is determined by the current in the transmission line. It is possible to reduce these losses by reducing the current in the transmission line by increasing the transmission voltage from the TS to the main step-up substation. To that end, TPs with a capacity of 1 MW are included in the structure of the SPP together with inverter converters. The results of the calculations of the electric power losses for transit are presented in Table 1.

Table 1. The power losses of electricity in the transmission lines

№	*U*	*I*	*L*	*R*	*P*	*N*	*P* total	*P* / *P* total
	kV	A	km	ohm	kW	pc.	kW	%
1	0,36	50	0,48	1,5	3,8	384	1459	50
2	0,4	300	2,64	0,61	54	24	1310	46
3	10	60	18	35,6	128	1	128	4
						Total	2900	

The transmission of electricity from modules to inverters is carried out at a constant current of 360V and the maximum current in the transmission line is 50 amps. The dimensions of one module are 30 x 30 m. The inverters are connected to the DC buses and the output voltage is 0.4 kV. The current in the nominal power mode reaches 300 amps. This distance does not exceed 160 m.

The transmission of the power from the TS to the main step-up substation is carried out on alternating current with voltage of 10 kV. The current in the transmission line reaches 60 A. The transmission distance does not exceed 1 km for SPP with a peak installed capacity of 24 MW.

The transit of electricity through the territory of the SPP at 10 kV voltage will reduce the losses of energy transmission by another 42 % as compared to direct current lines. The total transit losses are 3 MW and the peak output power will be 21 MW. The relative value of losses is 13.8 %, of which half is provided by DC transmission lines.

4. CONCLUSION

We can do the following conclusions from the above material:

1. There are 2, 3 or 4 voltage levels in the SPP structure depending on the total installed capacity of the modules. The optimal number of conversion stages is determined by the parameters of the power equipment.

2. The main step-up substation should be located in the CEG to reduce transmission losses in the power plant. The coordinates can be calculated by the methods for determining the CEL.

3. The method of distributed capacities allows to determine the unit capacity of power equipment - transformers, inverter converters and circuit breakers installed on the intermediate transformer substations and the main substations.

4. The use of the distributed power method allows you to determine the coordinates of both global and local

CEG, which can be used to install inverter converters and TS.

5. The SPP of the high capacity has a large territory and significant distance of sections from the route of regional distribution networks. The SPP may have several main step-up substations, which are several kilometres away.

6. On the basis of the local CEGs it is possible to construct a complex system of the connections in the SPP, which can be represented as a non-directional graph. Such a system will reduce the power losses in the SPP and use the capacities of the single generation facilities as efficiently as possible.

REFERENCES

[1] Zh.I. Alferov, V.M. Andreev, V.D. Rumyantsev, Trends and prospects for the development of the solar photoenergy, Physics and technology of the semiconductors. 2004. V. 38, No. 8. Pp. 937-948.

[2] Yu.D. Sibikin, M.Yu. Sibikin Non-traditional and renewable energy sources: Textbook. Moscow: KnoRus Publ. 2017, 240 p.

[3] The product catalog of the company «Silasolar». Text. Website https://e-solarpower.ru/solar/solar-panels/mono-panel/solnechnaya-batareya-silasolar-400vt-perc-5bb/ Free mode of access.

[4] A. Kolpakov. The circuitry of the powerful high-voltage converters. The power electronics. 2007. No. 2.

[5] The group of companies «Hevel» commissioned two solar power plants in the Turkestan region of the Republic of Kazakhstan. Text. Website: https://www.hevelsolar.com/about/news/dve-kazakhstan/. Free mode of access.

[6] A.A. Fedorov The fundamentals of the power supply of the industrial enterprises. M.: Energoatomizdat, 1984, 466 p

[7] S.A. Mikhailov, V.Ya. Goryachev, The mathematical methods of the determining the center of loads distributed over the surface, Fundamental research, No. 4, 2013. 276 p.