

Adequacy analysis of electric power systems with wind and solar power stations

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Abstract. We developed a new method of adequacy analysis of electric power systems with wind and solar power stations. There are storage batteries in the electric power system. Various types of storage batteries can be used in electric power systems. They are electrochemical, hydroelectric, heat or air storages. The modelling of wind speed and solar radiation is based on software «Local analysis of environmental parameters and solar radiation». The original combination of modern models of meteorological data processing is used in the software. For adequacy analysis of electric power system, we use nonsingle estimation of electricity sacrifice in random hour. Simulation of random values is carried out by the Monte Carlo method.

1 Introduction

Researches of adequacy of electric power systems are presented, for example, [1-5]. The method of adequacy analysis based on estimation of random states of electric power system was suggested in [4]. Simulation of random states in the method is carried out by the Monte Carlo method.

Modern electric power systems contain generators on renewable energy sources. Generation on wind and solar stations has random and oscillated character. Using of storage batteries in the such electric power system allows to stabilize of electricity supply. Applying of traditional method [4] for adequacy analysis of the electric power system is not possible. Modification of the method under modern conditions supposes high quality of meteorological data processing, modelling of charging and discharging processes, simulating of random values of solar radiation and wind speed.

Scientific researches of adequacy analysis of electric power systems with wind power generators and different storage batteries are presented in articles [9-19]. However, we concentrate our attention on a research of R. Billinton [13-15] and Y-F. Li [9-11, 16]. Integration of wind power stations and storage batteries in the system along with detailed describing of adequacy analysis is considered in these articles. We also give high estimation of research of Ungjin Oh [12]. Ungjin Oh fully described of charge and discharge processes of storage batteries under solving of the problem of adequacy analysis of electric power system with wind power plants and energy storages.

In spite of high level of presented articles, it is necessary to research of impact of a quality of meteorological data on a system reliability level. In particular, we need to analyze of possibility of an employing of a real meteorological data of FM 12

Synop и METAR to estimate of adequacy of electric power system with power generators on renewable sources and energy storages. In world practice they recommend to use Rayleigh and Weibull distributions for wind speed simulations [20-23].

The aim of our article consists in the development of a new method for adequacy analysis of electric power systems with renewable sources and storage batteries. Various types of storage batteries can be used in electric power systems. They are electrochemical, hydroelectric, heat or air storages. A storage hydroelectric power station is most used as energy storage in large electric power systems. We talk about important things in modelling of work of wind and solar power stations in the first part of our article. The second part of our article contains a description of a modification of the model of electricity shortage estimation. Quadratic losses of electricity under transmission are took into account in the model. Theoretical research of the model [24] speaks about the efficiency of applying of the model under adequacy analysis of electric power systems. We represented results of an experimental research of test scheme of electric power system with wind, solar power generators and storage batteries in the third part of the article. As an object of research we used a real long-term meteorological data from the Russkiy island.

2 Analysis of a long-term meteorological data

One of the most important problem in the modelling of renewable energy sources is a processing of long-term meteorological data. The quality of analyzing of long-term meteorological data impacts on estimation of electricity generation and main parameters of the regime of a wind or solar power station.

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We are going to simulate of wind speed and solar radiation on a base of the earlier developed method for a reproduction of the environment state in the considered location [25]. The given method was represented by software «Local analysis of environmental parameters and solar radiation». Long-term meteorological data of FM 12 Synop and METAR are used in the software.

2.1. The modelling of work of a wind power station

For the computing of generated power on a wind station we used the follow classical formula [22, 23]

$$P_w = \frac{s_w c_w \rho v^3}{2}. \quad (1)$$

where s_w is square of swept surface, m^2 , c_w is a power coefficient, p.u., ρ is air density, kg/m^3 , v is a wind speed, m/s . The aria of swept surface is computed by formula $s_w = \pi r^2$ for a wind power generator with horizontal axis of rotation where r is radius of wind wheel.

Air density with humidity is found by the follow rule

$$\rho = \frac{\rho_d R_v + \rho_v R_d}{R_d R_v t}. \quad (2)$$

here, ρ_d is partial pressure of dry air, Pa, R_d is a gas constant for dry air (287,058 J/kg·K), t is a temperature of outside air, K, ρ_v is a pressure of vapour, Pa, R_v is a pour constant (461,495 J/kg·K).

Revaluation of a wind speed to a height of wind wheel tower is realized by

$$v_2 = v_1 (h_2 / h_1)^\beta \quad (3)$$

where v_1 is a measured wind speed on a height of 10 m (h_1), v_2 is correct wind speed on a working height h_2 , β is a roughness coefficient of an underlying surface.

We analyzed of a wind power plant with horizontal axis of rotation «Enercon E-82 E2» in our research. «Enercon E-82 E2» is often used in littoral and offshore regions of European Union. The height of such wind power plant is equal 80 m and radius of the wind wheel is 40 m.

2.2. The modelling of work of a solar power station

Generated power (W) of a solar panel depends on solar radiation rate and square of working surface. We'll be able to compute generated power by the next formula

$$P_s = s_s c_s I_t. \quad (4)$$

where s_s is square of surface of the solar panel, m^2 , c_s is a power coefficient of the solar panel, p.u., I_t is a total solar radiation, W/m^2 .

Solar radiation incoming to Earth is inconstant and depends on many parameters. Geographic coordinates, time zone, amount of days of a considered period, the time of the sun's appearance and others are unvarying parameters. Composition of clouds, albedo of Earth's surface, atmospheric mass, thickness of ozone screen, spectral distribution of shine, existence of vapour and aerosol in clouds are variable parameters.

First of all, we find a time of rise, zenith and sunset for every day of a considered period on a selected territory. After that we compute of direct (I_b), diffuse (I_d) and total (I_t) solar radiation. A detailed description of a procedure of solar radiation computing is presented in [25].

Total solar radiation (W/m^2) is defined by the rule

$$I_t = (I_b + I_d) C_r. \quad (5)$$

Here C_r is a coefficient of decreasing of total solar radiation, $C_r = 1 - 0,75(N/8)^{3,4}$.

A value of cloudiness N depends on grade of clouds covering a sky in some moment of time [25].

2.3. The model of electricity shortage estimation

We consider a scheme of electric power system with n nodes and some set of system links. Let N is a given number of modeled hours of electric power system work. An every hour of electric power system work is characterized by a set of random values such as generated electricity \bar{x}_i^k in a node i , electricity demand \bar{y}_i^k in a node i and line capacity \bar{z}_{ij}^k between nodes i and j , $i = 1, \dots, n$, $j = 1, \dots, n$, $i \neq j$, $k = 1, \dots, N$.

It is set minimum $\overline{\Delta x}_i^{\min}$ and maximum $\overline{\Delta x}_i^{\max}$ capacity of a storage battery which located in node i . For k -th hour electricity reserve $\underline{\Delta x}_i^k$ and residual capacity $\overline{\Delta x}_i^k$ of a storage battery are computed on a base of previous computations, $i = 1, \dots, n$, $k = 1, \dots, N$.

Let x_i is electricity generated in a node i , Δx_i is change of accumulated electricity in storage battery in a node i , y_i is electricity consumption in a node i , z_{ij} is electricity transmitted from node i to node j , $i = 1, \dots, n$, $j = 1, \dots, n$, $i \neq j$.

The problem of electricity shortage estimation in k -th hour, $k = 1, \dots, N$, is written as:

$$G \sum_{i=1}^n y_i + \sum_{i=1}^n \Delta x_i \rightarrow \max, \quad (6)$$

$$x_i - y_i + \sum_{j=1}^n (1 - a_{ji} z_{ji}) z_{ji} - \sum_{j=1}^n z_{ij} - \Delta x_i = 0, \quad (7)$$

$$i = 1, \dots, n, \quad i \neq j, \quad (8)$$

$$0 \leq y_i \leq \bar{y}_i^k, \quad i = 1, \dots, n, \quad (9)$$

$$0 \leq x_i \leq \bar{x}_i^k, \quad i = 1, \dots, n, \quad (10)$$

$$-\underline{\Delta x}_i^k \leq \Delta x_i \leq \overline{\Delta x}_i^k, \quad i=1, \dots, n, \quad (11)$$

$$0 \leq z_{ij} \leq \overline{z}_{ij}^k, \quad i=1, \dots, n, \quad j=1, \dots, n, \quad i \neq j. \quad (12)$$

Here a_{ij} is a nonnegative coefficient of electricity losses under transmission from node i to node j , $i \neq j$, G is a high positive number. The weight coefficient G is necessary for mainstreaming of minimization of electricity shortage. Variables Δx_i can be negative. It means that electricity consumption is bigger than electricity generated in a current hour.

That's way electricity shortage is covered by means of consuming electricity from a storage battery. Let Δx_i^{k-1} is an optimal value of a variable Δx_i in the problem (1) – (6) for $(k-1)$ -th hour. Values $\underline{\Delta x}_i^k$ and $\overline{\Delta x}_i^k$, $i=1, \dots, n$, $k=2, \dots, N$, are computed recurrently $\underline{\Delta x}_i^k = \underline{\Delta x}_i^{k-1} + \Delta x_i^{k-1}$, $\overline{\Delta x}_i^k = \overline{\Delta x}_i^{\max} - \underline{\Delta x}_i^k$.

We suppose that a random value ζ_i is equally distributed on interval $[\overline{\Delta x}_i^{\min}, \overline{\Delta x}_i^{\max}]$, $i=1, \dots, n$. Any meaning of ζ can be used as Δx_i^0 , $i=1, \dots, n$.

The described process of charging and consuming of electricity from storage battery is Markov process [15]. We can consider an optimal solution of the problem (6) – (12) as equally probable for every hour. The problem (6) – (12) has a solution because its feasible set is not empty (the point $y_i=0$, $x_i=0$, $\Delta x_i=0$, $z_{ij}=0$, $i=1, \dots, n$, $j=1, \dots, n$, $i \neq j$, is feasible) and bounded according to (8) – (12), objective function is linear. Uniqueness of optimal values of y_i , $i=1, \dots, n$, is followed from theorems [10].

Simulation of random values is realized on their distributions. Reliability indices and procedures of their computing are also discussed in [8].

3 Experimental research

Experimental research of developed method was played out on a test example [8]. The scheme of electric power system consists of 5 nodes и 5 system links (a fig.1).

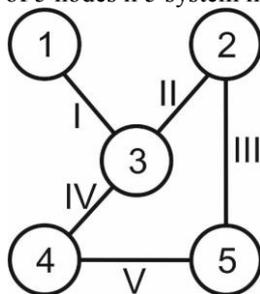


Fig.1. Scheme of electric power system

You'll be able to study of technical characteristics of the electric power system in a table 1. Nodes in the system are linked by electric transmission lines with voltage of 220 kV and a line capacity of 135 MW with an integral coefficient of an accident 0,011 p.u. by 100

km and a coefficient of electricity losses 0,0001661 p.u. Wind, solar power stations and storage batteries are located in the node №1 of the electric power system.

Table 1. Technical characteristics of the electric power system

A node №	Total power in a node, MW	Max; of load, MW	A link №	Quantity of power lines in a link	Length, km
1	600	700	I	2	200
2	1000	700	II	2	100
3	1400	1300	I & II	1	300
4	1000	1000	IV	2	200
5	1200	1100	V	2	300
Total	5200	4900	-	-	-

We have analyzed of meteorological data from the Russkiy island for modelling of wind speed and solar radiation. There are 1892160 observations.

Processing of long-term meteorological data showed that a wind direction is northerly for autumn and winter seasons in the research location. While a wind direction is southerly for spring and summer terms. We used of pressure of air, temperature, humidity for computation of air density. Air density has high meanings for autumn and winter seasons from behind of low temperatures, high atmosphere pressure and low humidity. Opposite meanings of air density are observed for spring and summer seasons. Monthly average wind speed of more 5 m/s on a height 10 m. is observed for autumn and winter seasons.

We presented of monthly average wind speed on a height 80 m. on a fig.2. You'll be able to see from a fig.2 that wind power plant would be worked in nominal regime from September through April.

Results of adequacy analysis of the electric power system with wind power station of 20 MW were obtained in [8]. Air density and storage batteries were not used in computation process of generated electricity. The probability of work without electricity shortage has meaning 0,994920 p.u. in this case. The mathematical expectation of electricity shortage is 0,196116 MWh.

We presented of results of computations of reliability indexes for the system with wind power plants and storage batteries in a table 2. A wind speed and volume of generated electricity were computed by described above formulas.

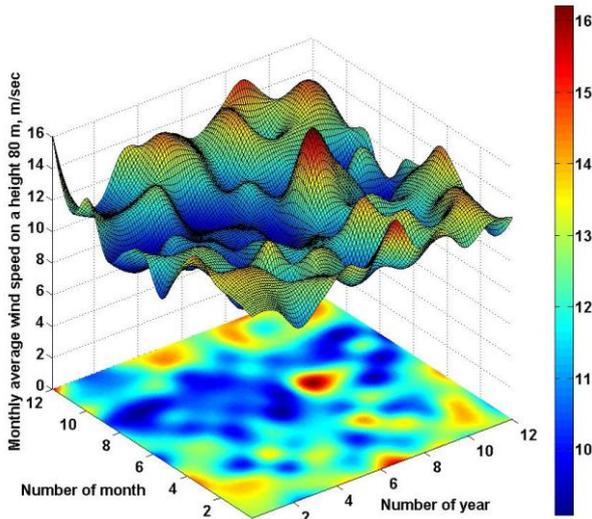


Fig. 2. Monthly average wind speed on a height 80 m., the Russkiy island.

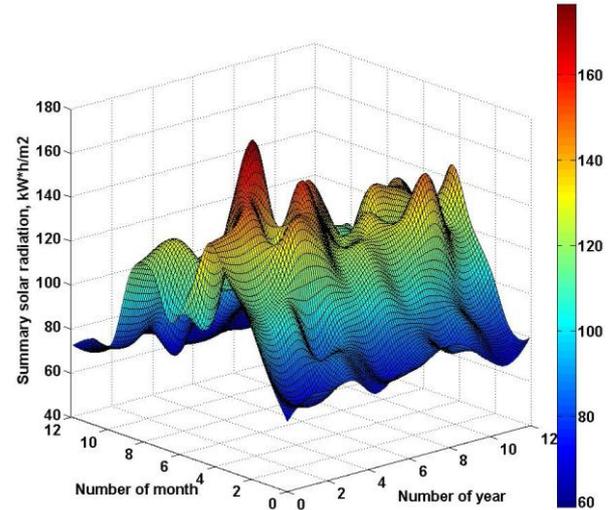


Fig. 3. Changing of solar radiation of the Russkiy island for twelve's year observations

Table 2. Reliability indexes of the electric power system with wind power plants and storage batteries

Structure of electric power system		The probability of work without electricity shortage, p.u.	The mathem; expectation of elec-ty shortage, MWh
Wind power plants, MW	Storage batteries, MWh		
20	-	0,995890	0,135934
	2	0,996120	0,147552
	4	0,996220	0,169415
	6	0,996630	0,123294

Complete accounting of environmental data allowed to obtain more valid reliability indexes. Integration of storage batteries also increased reliability level of the electric power system. Herewith we can place 20 MW of wind power plants and 2 MWh of storage batteries in the electric power system for obtaining of requested reliability level (0,996 for probability of work without electricity shortage). We presented of changing of solar radiation of the Russkiy island for twelve's year observations on a fig.3. You can see that solar radiation is most intensive from April through November. Results of adequacy estimation of electric power system with solar power plants and storage batteries are presented in a table 3.

Table 3. Reliability indexes of the electric power system with solar power plants and storage batteries

Structure of electric power system		The probability of work without electricity shortage, p.u.	The mathem; expectation of elec-ty shortage, MWh
Solar power plants, MW	Storage batteries, MWh		
10	-	0,995002	0,169478
	2	0,995501	0,131489
	10	0,996321	0,106480
	15	0,997403	0,095589

Results of experimental research confirm a fact that for using of solar power plants in electric power system we need bigger storage batteries.

4 Conclusion

The new model of adequacy analysis of electric power system with wind and solar power plants and storage batteries is presented in the article. We use the software «Local analysis of environmental parameters and solar radiation» for detailed modelling of environmental conditions on the considered territory. Complete accounting of environmental data increases of efficiency of modelling of power plants based on renewable sources. Results of our experimental research confirm of correctness of the above statement. Accounting of air density under modelling of wind power plants increases validity of reliability indexes. Integration of storage batteries into electric power systems with wind and solar power plants also increases reliability level and stabilizes of regime indexes. Herewith storage batteries are momentary power reserve. Increase of capacity of storage batteries leads to decrease the mathematical expectation of electricity shortage. Modelling of charging and discharging processes in a storage battery is presented in a view as Markov process. This fact allows to increase computational efficiency of the method.

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