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Improving the Methods for Optimization of Composition of Equipment in Autonomous Systems with Power Plants Based on Renewable Energy Resources

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ABSTRACT: In modern conditions of intensive increase in electricity consumption in all spheres of human activity, limited reserves of hydrocarbon fuel, as well as the severity of environmental problems in the energy sector, it is important to develop and implement more efficient methods for the construction and operation of power plants operating on renewable energy resources. The design of autonomous systems with stations using such energy resources involves, in particular, the selection of the optimal composition of the main equipment. Despite the current existence of a number of developments to solve this problem, the issues of improving them by taking into account all limiting and influencing factors, increasing the accuracy of optimization, remains as an urgent task.
This paper proposes an effective mathematical model and algorithm for optimization the composition of equipment in autonomous systems containing solar and wind power plants, as well as batteries, taking into account influencing factors. The proposed algorithm involves solving the problem by reducing it to a linear programming problem and using the simplex method. The results of a study of the effectiveness of the proposed model and optimization algorithm are presented. Based on the results of the calculation experiments performed, it was revealed that the proposed model and algorithm for optimization the composition of equipment in such an autonomous system has good computational quality and high calculation accuracy.

KEY WORDS: optimization, mathematical model, algorithm, autonomous system, photovoltaic station, wind power plant, solar module, wind unit, capital investment, operating costs.

I. INTRODUCTION

In modern conditions of intensive increase in electricity consumption in all spheres of human activity, limited reserves of traditional hydrocarbon energy resources, as well as the urgency of the problem of environmental protection, it is especially important to increase the share of renewable energy sources in the overall energy balance. A comprehensive solution to this problem requires, in particular, the identification of effective methods for producing electricity based on the use of renewable energy resources. Efficiency in this case is, first of all, determined by the rational design of power plants using these types of energy resources by optimization the composition of the equipment used.

This paper examines the problem of selecting the composition of equipment in an autonomous power system containing solar and wind stations (SFES and WPP), as well as a battery.

The existing literature contains a number of developments devoted to solving this problem, in particular [1-10], which undoubtedly made a great contribution to the development of the theory and methods for selecting the optimal configuration of equipment in power plants using renewable energy resources.

In [1], the results of a study of the issue of choosing the optimal configuration of equipment for a hybrid system based on wind and hydrogen plants are given. Two diagrams of the optimal configuration of a hybrid wind-hydrogen energy system in isolated mode are presented. The model described in this work involves the use of an evaluation optimization model. In [2], approaches for determining the configuration of systems with power plants using renewable energy resources, integrated in small electrical systems are proposed. The results obtained in it can be used to make a rational decision to determine the best configuration of electricity sources. In [3], a method for determining the optimal locations and capacity of power plants operating on renewable energy resources in regions with unreliable energy sources is given. In [4], scenarios for power supply to rural areas using photovoltaic, wind and pumped storage stations were studied. A

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mathematical description and algorithms for solving the problem of choosing the composition of the main equipment in such system are provided based on the use of heuristic methods implemented in the MATLAB environment.

The work [5] is devoted to the problem of choosing the optimal equipment configuration for a hybrid system consisting of solar and wind installations, as well as a battery. The results of solving the problem by two methods of artificial intelligence - the particle swarm algorithm and the genetic algorithm are given. As a result the second algorithm is recommended as more effective for solving the problem under consideration. The optimized parameters, in accordance with the mathematical model used in this work, are the power of the installations. Therefore, the direct application of the model and algorithm described in it for selecting the composition of equipment in stations using renewable energy resources is associated with solving additional problems. In [6], the issues of choosing the optimal configuration of hybrid power plants operating on the basis of renewable energy resources were studied. In [7], the results of assessing the composition of equipment in an autonomous hybrid system with wind, solar and diesel plants, which serve to supply energy to three health care institutions in rural areas of Nigeria are presented. The results of similar work on optimization the configuration of a hybrid system, including solar, wind and diesel stations in the Saudi Arabia region, are given in [8]. These works do not present the mathematical models and methods used to solve the problem. Important scientific results devoted to the effective solution of the problem under consideration are given in [9]. It provides a mathematical model and algorithm for solving the problem of optimization the configuration of an autonomous hybrid system containing solar and wind installations as well as a battery. According to the described algorithm, the problem is solved in two stages. At the first stage, based on the minimization of the objective function, which is a function of the probability of a power failure, various options for the configuration of system equipment are determined. And at the second stage, by minimization the cost function taking into account constraints on the reliability of power supply, the most optimal configuration option is determined. Despite the fact that the method described in this work is more effective compared to other methods considered for solving the problem considered here, it remains important to improve the described method in the direction of increasing accuracy through the joint solution of problems considered separately in two stages. In [10], a mathematical model and algorithm for selecting the optimal sizes of systems that include solar and wind installations operating in parallel with the electric power system (EPS) are proposed. However, the described model and the calculation algorithm based on it cannot be used to select the optimal composition of equipment in autonomous hybrid systems.

In this regard, the problem of developing and implementing effective models and algorithms for optimization the composition of equipment of power plants operating on renewable energy resources, taking into account all limiting and influencing factors, remains an urgent task. This paper proposes a new effective mathematical model and algorithm for solving the problem of optimization the composition of equipment in an autonomous power system containing solar power plants, wind farms and batteries, which are a development of the work performed in this direction by the authors of this material [11-13].

II.MATERIALS AND METHODS

Mathematical model and optimization algorithm.

The schematic diagram of the autonomous system under consideration, which contains solar photovoltaic power plant (SPPP), wind power plant (WPP) and battery storage (BS), can be represented as shown in Fig. 1.

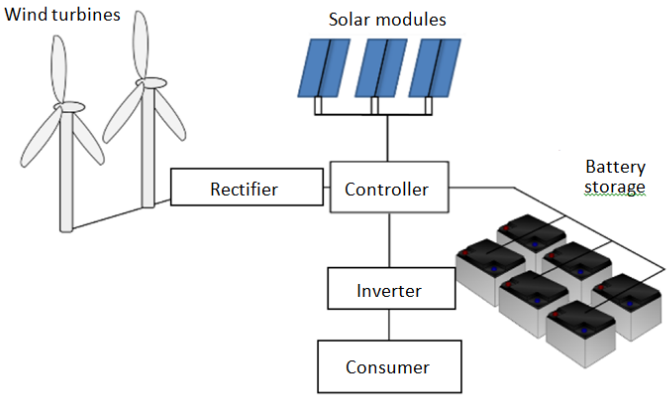

Fig.1. Schematic diagram of an autonomous system containing SPPP, WPP and BS.

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The mathematical model of the problem of optimization the composition of equipment of an autonomous system, which includes a SPPP, WPP and BS, can be formulated as follows:

- minimize the objective function, which represents the total costs associated with the construction and operation of the system during the operating period T

$$Z = Z_{PV} + Z_W + Z_{BS} + Z_{BOS} = \left(1 + k_{PV.OM}\right) \cdot C_{PV} \cdot N_{PV} + \\ + \left(1 + k_{W.OM}\right) \cdot C_W \cdot N_W + \left(C_{BS} + C_{BS.rep.}\right) \cdot N_{BS} + Z_{BOS} \to \min \quad (1)$$

taking into account constraints:

- on power balance in each time interval of the period under consideration T

$$P_{PV}^{(t)} + P_W^{(t)} + P_{BS}^{dch(t)} = P_L^{(t)} + P_{BS}^{ch(t)}, \quad t = 1, 2, ..., T; \quad (2)$$

- on permissible minimum and maximum power of solar modules and wind units

$$P_{PV}^{min} \le P_{PV}^{(t)} \le P_{PV}^{max}, \quad t = 1, 2, ..., T; \quad (3)$$

$$P_W^{\min} \le P_W^{(t)} \le P_W^{\max}, \quad t = 1, 2, ..., T; \quad (3a)$$

- on permissible minimum and maximum charging power of the battery storage

$$0 \le P_{BS}^{ch(t)} \le P_{BS}^{ch.max}, \quad t = 1, 2, ..., T; \quad (4)$$

$$0 \le P_{BS}^{dch(t)} \le P_{BS}^{dch.max}, \quad t = 1, 2, ..., T; \quad (4a)$$

- on permissible minimum and maximum energy (capacity) of battery charge

$$W_{BS}^{(t)min} \le W_{BS}^{(t)} \le W_{BS}^{(t)max}, \quad t = 1, 2, ..., T; \quad (5)$$

where T is the number of time intervals during the period under consideration; Z_{PV}, Z_W, Z_{BS}, Z_{BOS} are the amount of capital investments and operating costs for solar modules, wind units, battery storage and other conversion, control and recording installations, respectively; C_{PV}, C_W, C_{BS} are specific capital investments for solar modules, wind units and batteries; $C_{BS.rep.}$ is specific capital investments associated with replacing the battery; $k_{PV.OM}$, $k_{W.OM}$ are specific operating costs for the solar module and wind unit, respectively; N_{PV}, N_W, N_{BS} are number of solar modules, wind units and batteries; $P_{PV}^{(t)}$, $P_W^{(t)}$, $P_{BS}^{ch(t)}$, $P_{BS}^{dch(t)}$ are the total power of solar modules, wind units and the charging and discharging power of batteries in the t-th time interval of the period under consideration, respectively; $P_{BS}^{ch.max}, P_{BS}^{dch.max}$ are permissible maximum charging and discharging power of the battery; $W_{BS}^{(t)}, W_{BS}^{(t)min}, W_{BS}^{(t)max}$ are the amount of energy in the battery storage in t-th time interval, as well as its permissible minimum and maximum values; $W_{BS.\text{отд.}}^{(t)}, W_{BS.\text{пол.}}^{(t)}$ are the amount of electricity given due to discharge and received due to charge the battery storage by the t-th time interval.

As a result of solving the problem under consideration, in particular, the optimal number of solar modules N_{PV}, wind units N_W and batteries N_{BS} are determined. Therefore, when solving the problem using the given mathematical model, we express the parameters in the limiting conditions through these unknowns. The power of solar modules and wind units in the t-th time interval can be determined as follows [9]:

$$P_{PV}^{(t)} = R_{sol}^{(t)} \cdot A \cdot N_{PV} \cdot \eta_{PV}^{(t)} \cdot \eta_{El}, \quad (6)$$

$$P_W^{(t)} = \left(av^{(t)3} + bv^{(t)2} + cv^{(t)} + d\right) \cdot \eta_W^{(t)} \cdot \eta_{El} \cdot N_W, \quad (6a)$$

Where $R_{sol}^{(t)}$ is the specific power of incident solar radiation; A is the surface area of one solar panel; , $\eta_{PV}^{(t)}$, $\eta_W^{(t)}$ efficiency of solar modules and wind turbines in the t-th time interval; η_{El} is the efficiency of electronics system, which serves to ensure reliable operation of solar and wind power plants. According to [14] η_{El} = 0.98; $v^{(t)}$ is wind speed in the t-th time interval; a, b, c, d are the constant coefficients of the cubic polynomial obtained by approximation the dependence of $P_W(v)$ specified by the manufacturer in tabular form.

The amount of energy in the battery by the t-th time interval $W_{BS}^{(t)}$ can be determined as follows:

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$$W_{BS}^{(t)} = W_b + \sum_{i=1}^{t} P_{BS}^{ch(i)} - \sum_{i=1}^{t} \frac{P_{BS}^{dch(i)}}{\eta_{BS}^{(i)}}, \tag{7}$$

where W_b is the residual energy in the battery at the beginning of the period under consideration, when t=0; $\eta_{BS}^{(i)}$ is the battery efficiency in the *i*-th time interval.

According to expressions (6) and (6a), constraints (3) and (3a) can be presented in the following form:

$$P_{1PV}^{min} \cdot N_{PV} \le R_{sol}^{(t)} \cdot A \cdot N_{PV} \cdot \eta_{PV}^{(t)} \cdot \eta_{El} \le P_{1PV}^{max} \cdot N_{PV}, \tag{3b}$$

$$P_{1W}^{\min} \cdot N_W \le \left(av^{(t)3} + bv^{(t)2} + cv^{(t)} + d\right) \cdot N_W \le P_{1W}^{\max} \cdot N_W, \tag{3c}$$

where $P_{1PV}^{\min}$, $P_{1PV}^{\max}$, $P_{1W}^{\min}$, $P_{1W}^{\max}$ are minimum and maximum permissible power of one solar module and one wind turbine. Dividing inequalities (3b) and (3c) by N_{PV} and N_W, respectively, we obtain conditions that do not depend on the number of solar modules and wind units. This shows that constraints (3) and (3a) do not affect the result of solving the problem under consideration. Therefore, in the mathematical model of the problem we exclude these constraints.

Constraints on the permissible minimum and maximum charging and discharging powers of batteries (4) and (4a) can be presented in the following form:

$$0 \le P_{BS}^{ch(t)} \le P_{1BS}^{ch.max} \cdot N_{BS}, \quad t = 1, 2, ..., T; \tag{8}$$

$$0 \le P_{BS}^{dch(t)} \le P_{1BS}^{dch.max} \cdot N_{BS}, \quad t = 1, 2, ..., T, \tag{9}$$

where $P_{1BS}^{ch.max}$, $P_{1BS}^{dch.max}$ are permissible maximum charging and discharging power of one battery in storage. By analogy with those obtained above, constraint (5) can be described as follows:

$$W_{1BS}^{\min} \cdot N_{BS} \le W_b + \sum_{i=1}^{t} P_{BS}^{ch(i)} - \sum_{i=1}^{t} \frac{P_{BS}^{dch(i)}}{\eta_{BS}^{(i)}} \le W_{1BS}^{\max} \cdot N_{BS}, \quad t = 1, 2, ..., T, \tag{10}$$

where W_{1BS}^{min}, W_{1BS}^{max} are the minimum and maximum permissible values of electricity that can be accumulated in one battery. In the case under consideration, we assume that at the end of the period under consideration (when *t*=*T*) the residual electricity in the battery will be the same as at the beginning of the period W_b. In this case, to ensure the fulfillment of this condition, to the number of constraints taken into account in the form of equality the following conditions are added:

$$\sum_{i=1}^{T} P_{BS}^{ch(i)} - \sum_{i=1}^{T} \frac{P_{BS}^{dch(i)}}{\eta_{BS}^{(i)}} = 0, \tag{11}$$

where $\sum_{i=1}^{T} P_{BS}^{ch(i)} = W_{BS.пол.}^{(T)}$ is the amount of electricity received by the battery storage during the period *T* due to charging; $\sum_{i=1}^{T} \frac{P_{BS}^{dch(i)}}{\eta_{BS}^{(i)}} = W_{BS.отд.}^{(T)}$ is the amount of electricity supplied to the battery storage during the period *T* due to discharge.

Currently, the standard service life of many solar modules, wind units and other conversion, control, registration and connection installations is 25 years [9, 15]. At the same time, the standard service life of gel batteries can be taken as 10 years. The costs associated with replacing the battery, reduced to current prices, can be determined by the formula

$$C_{BS.rep} = k_{pr.rep} \cdot C_{BS} = \frac{1}{(1 + k_{dis})^n} \cdot C_{BS}, \tag{12}$$

where $k_{pr.rep}$ is the coefficient of reduction of specific capital investments in the future to current prices; k_{dis} is the discount factor that determines the degree of reduction in specific capital investments during replacement, which is assumed to be 5.15%; *n* is the serial number of the year the battery was replaced from the start of its operation. Accordingly, when bringing the specific capital investment for a battery to 25 years, one should take into account its replacement 2 times, i.e. in the 10th and 20th years of operation, and residual value:

$$k_{pr.rep}=\frac{1}{1{,}0515^{10}}+0{,}5\cdot\left(\frac{1}{1{,}0515^{20}}+\frac{1}{1{,}0515^{30}}\right)=0{,}9\,.$$

Thus, $C_{BS.rep} = 0{,}9\cdot C_{BS}$. (13)

The number of batteries in one battery branch is determined in accordance with the rated voltages of the U_{net} network and one battery U_{1BS}:

$$N_{BS.ser.}=\frac{U_{net}}{U_{1BS}}\,. \tag{14}$$

The number obtained by the last formula is rounded up. The total number of batteries in the storage is determined by multiplying the number of branches connected in parallel with $N_{BS.par.}$ batteries and the number of $N_{BS.ser}$ batteries connected in series in each of branches:

$$N_{BS}=N_{BS.par.}\cdot N_{BS.ser.}\,. \tag{15}$$

According to [15, 16, 18], the annual operating costs for solar modules can be assumed to be 2.5% of the capital investment. In addition, when determining these costs, one should take into account the coefficient of reduction of future costs to current prices, defined as in [9, 17]:

$$k_{pr.PV}=\frac{(1+k_{dis})^{N}-1}{k_{dis}\cdot(1+k_{dis})^{N}}=\frac{1{,}0515^{25}-1}{0{,}0515\cdot 1{,}0515^{25}}=13{,}88\,. \tag{16}$$

Thus, $k_{PV.OM} = 0{,}025*13{,}88=0{,}347$.

Operating costs for wind turbines are 0,019-0,027 \$/kWh. In simplified calculations, annual operating costs can be taken as 2% of the capital investment [15], and the discount factor is 0.0515. In this case, the coefficient for converting future operating costs to current prices is the same as for solar modules (16) and, accordingly $k_{W.OM} = 0{,}278$.

The capital investment and operating costs for the remaining installations Z_{BOS} can be expressed as depended on their values for solar modules and wind turbines. They can be taken as in [9] $Z_{BOS} = 0{,}5\cdot(З_{PV}+З_{W})$.

Thus, the problem under consideration is mathematically formulated as follows:

objective function –

$$Z=1{,}847\cdot C_{PV}\cdot N_{PV}+1{,}778\cdot C_{W}\cdot N_{W}+1{,}9\cdot C_{BS}\cdot N_{BS.ser.}\cdot N_{BS.par.}\rightarrow\min\,; \tag{17}$$

constraints –

$$\begin{aligned}&R_{sol}^{(t)}\cdot A\cdot N_{PV}\cdot\eta_{PV}\cdot\eta_{El}+\left(av^{(t)3}+bv^{(t)2}+cv^{(t)}+d\right)\cdot\eta_{W}^{(t)}\cdot\eta_{El}\cdot N_{W}-\\&-P_{BS}^{ch(t)}+P_{BS}^{dch(t)}=P_{L}^{(t)},\quad t=1,2,\dots,T\end{aligned}; \tag{18}$$

$$0\le P_{BS}^{ch(t)}\le P_{1BS}^{ch.max}\cdot N_{BS.ser}\cdot N_{BS.par},\quad t=1,2,\dots,T\,; \tag{19}$$

$$0\le P_{BS}^{dch(t)}\le P_{1BS}^{dch.max}\cdot N_{BS.ser}\cdot N_{BS.par},\quad t=1,2,\dots,T\,, \tag{19a}$$

$$\begin{aligned}&W_{1BS}^{\min}\cdot N_{BS.ser}\cdot N_{BS.par}\le W_{b}+\sum_{i=1}^{t}P_{BS}^{ch(i)}-\sum_{i=1}^{t}\frac{P_{BS}^{dch(i)}}{\eta_{BS}^{(i)}}\le\\&\le W_{1BS}^{\max}\cdot N_{BS.ser}\cdot N_{BS.par},\quad t=1,2,\dots,T,\end{aligned} \tag{20}$$

$$\sum_{i=1}^{T}P_{BS}^{ch(i)}-\sum_{i=1}^{T}\frac{P_{BS}^{dch(i)}}{\eta_{BS}^{(i)}}=0\,, \tag{21}$$

At known graphs of incident of solar radiation and wind speed, the resulting problem (17)-(21) is reduced to a linear mathematical programming problem. Therefore, to solve it, you can use the simplex method. A block diagram of the algorithm for solving the problem based on the simplex method is shown in Fig. 2.

Based on the solution of the problem, the optimal values of all *3+2T* parameters N_{PV}, N_{W}, $N_{BS.par.}$ and $P_{BS}^{ch(1)}$, $P_{BS}^{ch(2)}$, ..., $P_{BS}^{ch(T)}$, $P_{BS}^{dch(1)}$, $P_{BS}^{dch(2)}$, ..., $P_{BS}^{dch(T)}$ are found. The number of solar modules, wind units and parallel branches with series connected batteries are determined by rounding the corresponding N_{PV}, N_{W}, $N_{BS.par}$ to the nearest integer. Then, using formula (15), the total number of batteries in the battery is determined.

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III. RESULTS AND DISCUSSIONS

The effectiveness of the proposed mathematical model and algorithm was studied in the example of choosing the composition of solar modules, wind units and batteries in an autonomous system that supplies an electric consumer, operating with a given daily load schedule.

Daily schedule of consumer load, specific power of incident solar radiation and wind speed are given in Table 1.

As an example, two types of solar modules, a wind turbine and a battery were selected. Below the results of intermediate calculations for one (first) type of equipment are presented.

Parameters of the selected type of solar module:

Place of production: Anhui, China; Model Number: SUN410-430 DE21M; Type: PERC, Shingled Solar Panel, Monocrystalline Silicon; service life: 25 years; maximum power: P_{1PV} = 415 W; panel surface size: 1723x1134 mm; efficiency: 20%; specific cost: C_{1PV} =0.19 $/W.

Wind turbine type parameters:

Model: SWG EW-1000; rated power: 1 kW; energy generation start speed: 3.5 m/s; design operating speed: 12 m/s; rotation speed: 450 rpm, clockwise; unit cost: $1000/piece; The power curve (dependence of output power on wind speed) is given in Table 2.

Battery parameters:

Place of production: Guangdong, China; Model Number: GE100AH/ 12V(100); type: Gel Lead Battery; service life: 10 years; Battery size: 12V, 100AH; maximum charging current: = 10 A; specific cost of battery: $91/piece.

In calculations, the efficiency of the battery in all time intervals is assumed to be $\eta_{BS}^{(i)}$ =0.85.

Table 1. Graphs of consumer loads, specific power of solar radiation incident and wind speed.

t, h.	1	2	3	4	5	6	7	8	9	10	11	12
	13	14	15	16	17	18	19	20	21	22	23	24
P_L, kW	7,6	5,8	4,7	5,6	6,3	9,2	12,6	17,5	22,4	27,3	30,4	26,7
	23,2	20,3	24,5	25,2	28,7	31,2	35,0	36,0	32,3	26,5	18,6	12,5
$R_{sol}^{(t)}$, kW/m^2	0,0	0,0	0,0	0,0	0,02	0,08	0,35	0,40	0,45	0,52	0,65	0,76
	0,85	0,86	0,80	0,65	0,54	0,25	0,05	0,0	0,0	0,0	0,0	0,0
$v^{(t)}$, m/s	5,6	5,3	5,4	4,6	4,8	4,7	4,9	5,0	5,6	3,6	3,5	2,5
	2,9	3,9	4,8	4,1	3,9	4,4	5,3	5,0	6,3	6,0	5,2	6,2

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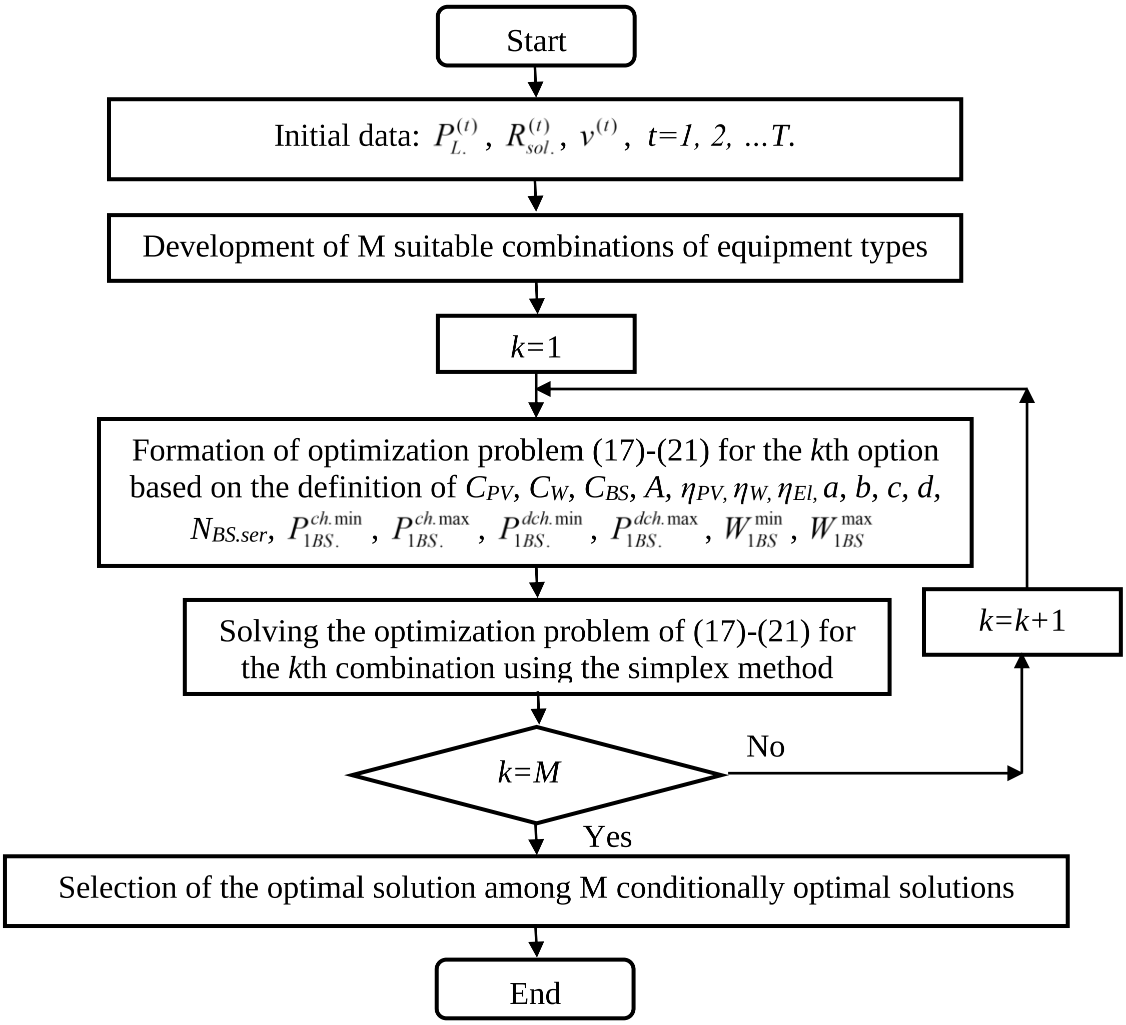

Fig. 2. Enlarged block diagram of the algorithm for optimization the composition of equipment.

Table 2. Power curve for wind turbine type EW-1000.

v, m/s	3,5	4,0	5,0	6,0	7,0	8,0	9,0	10,0	11,0	12,0
P_W, kW	0,04	0,06	0,10	0,15	0,25	0,35	0,47	0,62	0,85	1,10

To formulate the optimization problem, the corresponding parameters of its mathematical model (17)-(21) are determined. The rated voltage of the electrical network is 220 V. In accordance with this and according to (14), we have $N_{BS.ser}$ = 20 pcs. Accordingly, in the example under consideration we have

$$P_{BS}^{ch.\max} = P_{1.BS}^{ch.\max} \cdot N_{BS.ser} \cdot N_{BS.par} = 12\ B \cdot I_1^{ch.\max} \cdot 20\ uum. \cdot N_{BS.par} = 2{,}4 N_{BS.par}.$$

The maximum discharge current for gel batteries is approximately 10 times greater than the maximum charge current. Taking this into account, we can take $I_1^{dch.\max}$ = 100 A and similarly obtain the expression for the maximum discharge power: $P_{BS}^{dch.\max} = 24 N_{BS.par}$.

Based on similar calculations, we obtain an expression for the maximum battery charge energy $W_{BS}^{\max} = 24 N_{BS.par}$. And we find the expression for the minimum permissible charge energy based on the condition of the permissible depth

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of discharge of the battery 20%: $W_{BS}^{\min} = 4{,}8 N_{BS.par}$. The minimum and maximum permissible battery charge energies in all time intervals are assumed to be the same.

Cost of one solar module: $C_{PV}=C_{1PV}*P_{1PV}$= 415*0,19= 78,85 $.

The optimal number of solar modules obtained as a result of solving the problem based on the use of the proposed mathematical model and calculation algorithm: N_{PV} = 152 pcs. Optimal number of wind units: N_W =44 pcs. The optimal number of parallel-connected branches with 20 batteries in each: $N_{BS.pa}$ = 13 pcs. Accordingly, the total number of batteries in storage according to (15): N_{BS} = 20x13 = 260 pcs. Minimum value of the objective function: Z_{min} = 146.06 thousand $.

In Table 3 and Fig. 3 the optimal load schedules of solar power plant, wind farms and charging and discharging the battery storage at time intervals of the day obtained as a result of solving the problem are shown.

The charging and discharging power of the battery at each point of time, shown in the graph in Fig. 3, defined as $P_{dch}(t) = P_{BS}^{dch}(t) - P_{BS}^{ch}(t)$.

Table 3. Optimal load schedules for the consumer, solar power plant, wind farm and battery storage charging and discharging.

t, h.	1	2	3	4	5	6	7	8	9	10	11	12
	13	14	15	16	17	18	19	20	21	22	23	24
P_L, kW	7,6	5,8	4,7	5,6	6,3	9,2	12,6	17,5	22,4	27,3	30,4	26,7
	23,2	20,3	24,5	25,2	28,7	31,2	35,0	36,0	32,3	26,5	18,6	12,5
$P_{PV}^{(t)}$, kW	0,00	0,00	0,00	0,00	1,16	4,66	20,37	23,28	26,19	30,27	37,84	44,24
	49,48	50,06	46,57	37,84	31,43	14,55	2,91	0,0	0,00	0,00	0,00	0,00
$P_W^{(t)}$, kW	5,56	4,92	5,13	3,59	3,94	3,76	4,11	4,28	5,56	1,88	1,71	0,00
	0,00	2,40	3,94	2,74	2,40	3,25	4,92	4,28	7,70	6,42	4,71	7,27
$P_{BS}^{ch.(t)}$, kW	0,00	0,00	0,43	0,00	0,00	0,00	11,88	10,06	9,36	4,85	9,15	17,54
	26,28	32,16	26,00	15,38	5,13	0,00	0,00	0,00	0,00	0,00	0,00	0,00
$P_{BS}^{dch.(t)}$, kW	2,04	0,88	0,00	2,01	1,20	0,78	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00	0,00	13,40	27,17	31,72	24,60	20,08	13,89	5,23

Similar calculations were also performed for another (second) selected type of equipment. Table 4 shows the results of solving the problem for two selected types of equipment.

The optimal load schedules for photo electric module (PHEM), wind turbine and battery storage charging/discharging for the second option of equipment are shown in Fig. 4.

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Table 4. Results of optimization the equipment composition for two combinations of their types.

№	Equipment type			Optimal amount of equipment			Z, thouzand $
	PHEM	Wind turbine	BS	PHEM	Wind turbine	BS	
1.	SUN-410-430 DE21M	SWG EW-1000	GE100AH/ 12V(100)	152	44	260	146.06
2.	PNG-144M (182MM)	ATO-WT-400M2	GL-12-200	113	178	140	321.00

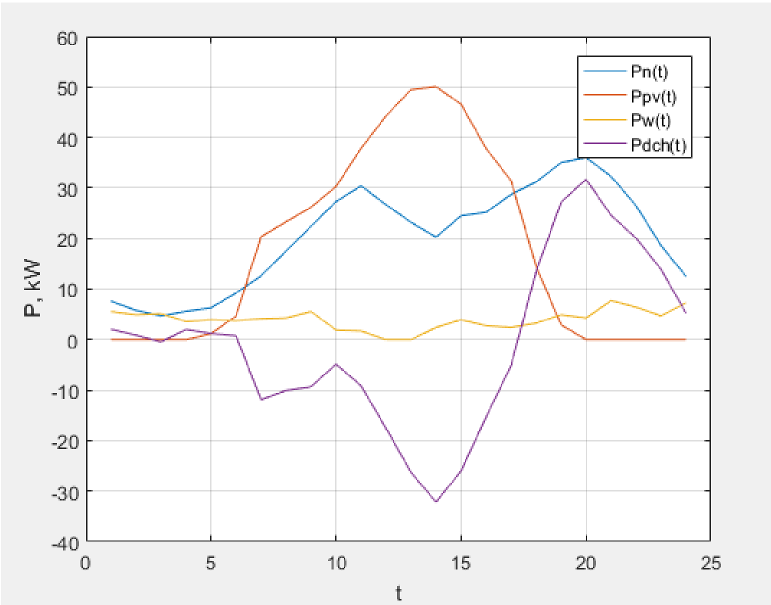

Fig.3. Optimal load schedules for the consumer, solar power plant, wind farm and battery charging and discharging (for the first option of equipment type).

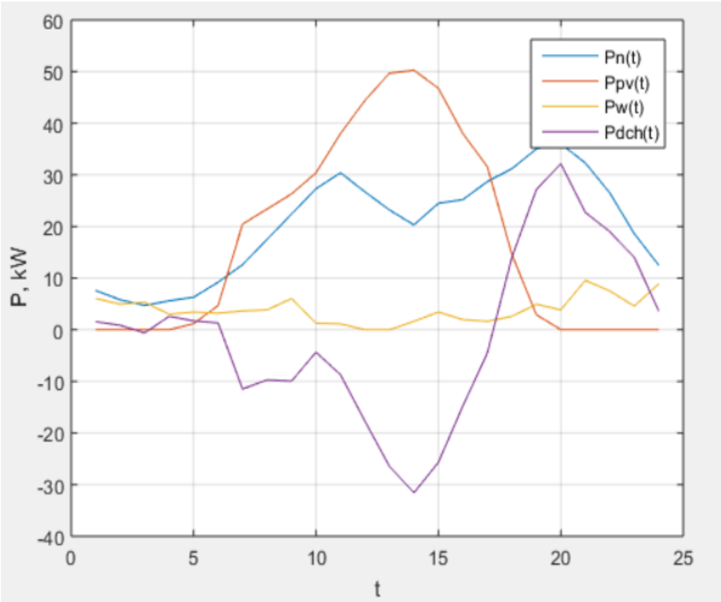

Fig.4. Optimal load schedules for the consumer, solar power plant, wind farm and battery charging and discharging (for the second option of equipment type).

Thus, the first type of equipment is rational; the estimated reduced costs for the full operating cycle are 146.06 thousand $, which is more than two times less than when using the second type of equipment.

The reliability of the obtained optimization result was verified by comparing it with a set of randomly selected feasible solutions. For all randomly selected solutions, the values of the objective function were obtained greater than when optimized using the proposed model and calculation algorithm.

According to the graphs shown in Fig. 3 and 4 we see the provision of power balance in the system in each time interval of the regulation cycle, taking into account all other constraints. If in some time intervals the total load of consumers is equal to the sum of the powers of the solar power plant, wind power plant and the discharge power of the battery, then in other time intervals the total power of the plants is equal to the sum of the load of consumers and the charging power of the battery. In addition, it is notable that the total charging energy of the battery storage during the regulation cycle is equal to the sum of the discharge energy and energy loss in it, which is 15%.

IV.CONCLUSION

1) A mathematical model for the problem of optimization the composition of equipment in an autonomous system containing a solar photovoltaic plant, a wind power plant and a battery storage, taking into account limiting conditions and losses in the system elements is proposed.

2) An algorithm for solving the problem of optimization the composition of equipment in an autonomous system, based on reducing it to a linear programming problem and using the simplex method is proposed.

3) Based on the calculation experiments performed on a specific example, it was established that the proposed model and algorithm for optimization the composition of equipment in an autonomous system has good computational quality and calculation accuracy.

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