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A METHOD FOR DESIGN OF THE OPTIMAL STRUCTURE OF AUTONOMOUS DISTRIBUTED HYBRID ENERGY COMPLEXES, AND REGULATION OF THE ENERGY BALANCE THEREIN

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The paper offers a method for developing a universal system of automated design of an optimal structure of autonomous distributed hybrid energy complexes (ADHEC) and a means of regulation of the energy balance therein, i.e. control of the power flows circulating in the said system. In general, the design of the optimal structure of ADHEC includes the following stages (subtasks): data research and creation of a statistical database of electric loads of consumers, of the wind speed in the region under consideration, of the hydroelectric potential of mountain and lowland rivers, and of the solar energy, as well as research and development of a database of converters of wind and water energy into electrical energy. The paper dwells on the task of designing the optimal structure of the distributed hybrid generation system that will ensure the desired level of power generation at a minimal cost and with necessary functional reliability.

Keywords: renewable energy sources, autonomous distributed hybrid energy complex, energy balance, functional reliability, control system, optimal structure; directed graph.

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ние аппарата сетей Петри для составления самоорганизующихся многокомпонентных вычислительных алгоритмов для решения задач в электро- и гидроэнергетике

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Introduction

With the development of society, the deficit of electrical energy (generated, as a rule, in the traditional way), increases, which leads to a decrease of functional reliability in its transmission and distribution to consumers in the required amounts. To resolve this problem, i.e. to decrease the load of the existing energy systems, increased attention has been given worldwide to the development and use of renewable (non-traditional) sources of energy (renewable energy sources, RES) [1-15] which are geographically dispersed and are volatile by nature.

In consideration of the above, this paper is devoted to the development of a theoretical and methodological basis for the design of autonomous energy complexes, including the following main tasks:

- Research and creation of a database of statistical data on electrical loads of consumers;
- study of RES in various regions, and the creation of a statistical database thereof;

- development of efficient converters of RSE into electrical energy from the standpoint of efficiency factor, reliability, and cost, and creation of a knowledge database thereof based on the existing and newly developed converters [1-17];
- development of a theoretical and methodological basis for the design of autonomous distributed hybrid energy complexes (ADHEC) that would be efficient in terms of structural and functional reliability and cost (self-sufficiency);
- development of effective ADHEC energy balance management systems;
- development of computer-aided automated design systems for ADHEC.

The paper makes a primary attempt to formalize the abovementioned tasks with a view to further in-depth detailing and development of universal computer-aided design (CAD) system for the design of the optimal structure of ADHEC. The main mathematical apparatus used for the development of ADHEC CAD system is the theory of computational Petri nets (CPN) [18, 19], which is an extension of the classical theory of Petri nets [20, 21].

List of symbols	
ADHEC	autonomous distributed hybrid energy complexes
CAD	computer-aided design
CPN	computational Petri nets
WG	wind generators
HG	hydraulic generators
SC	solar cell system
ES	electrical power consumers
SB	storage batteries
LPS	local power system
DG	diesel generator
GN	global (national) network
CC	control center
N_1, N_2	nodes for connecting power lines

1. General scheme of an autonomous distributed hybrid energy complex and the method of control of the energy balance therein.

The ADHEC scheme is shown in Fig. 1 in the form of a directed graph.

It consists of the following elements:

- *WG* – a distributed system of wind generators that generates power $W_{WG}(t)+\Delta W_{WG}(t)$, where $\Delta W_{WG}(t)$ - auxiliary power used for own needs, and $W_{WG}(t)$ - power supplied to the ADHEC system.
- *HG* – a distributed system of hydraulic generators generating power $W_{HG}(t)+\Delta W_{HG}(t)$, where $\Delta W_{HG}(t)$ - auxiliary power used for own needs and $W_{HG}(t)$ - power supplied to the ADHEC system.

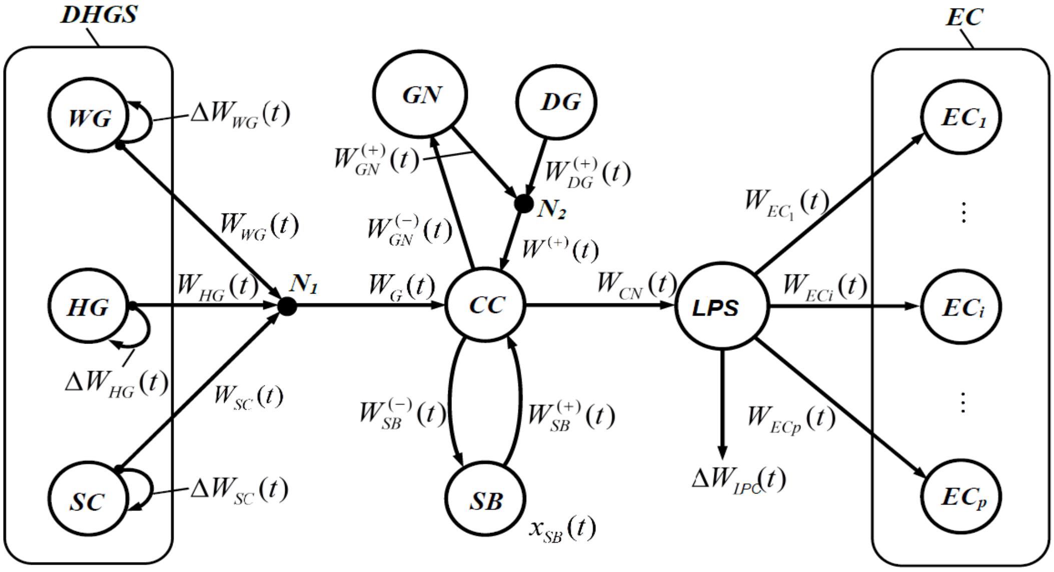

Fig. 1. General scheme of an autonomous distributed hybrid energy complex (ADHEC)

- *SC* – distributed solar cell system that generates power $W_{SC}(t)+\Delta W_{SC}(t)$, где $\Delta W_{SC}(t)$ - auxiliary power used for own needs and $W_{SC}(t)$ - power supplied to the ADHEC system.

- $\{WG, HG, SC\}$ – distributed hybrid generation system (DHGS), with the total power of

$$W_G(t) = W_{WG}(t) + W_{HG}(t) + W_{SC}(t); \qquad (1)$$

- $EC = \{EC_i \mid i \in N_{EC}\}$ – an aggregate of electrical power consumers with the consumed powers $\{W_{ECi}(t) \mid i \in N_{EC}\}$;, respectively; the total consumed power is as follows:

$$W_{EC}(t) = \sum_{i \in N_{EC}} W_{ECi}(t),$$
$$N_{EC} = \{1, 2, ..., p\}; \qquad (2)$$

- SB - a system of storage batteries, with the accumulated amount of electrical energy $x_{SB}(t)$ varying within the following:

$$x_{SB}^{min_{SBSB}^{max}}; \qquad (3)$$

The purpose of the storage battery is to store the excessive power $W_{SB}^{(-)}(t)$ eventually generated in the ADHEC system and to release the power $W_{SB}^{(+)}(t)$ back into the ADHEC system when the power deficiency occurs.

- *LPS* – local power system of the ADHEC system, intended for transportation and distribution of the required power $W_{CN}(t)$ to consumers:

$$W_{CN}(t) = W_{EC}(t) + \Delta W_{LPS}(t); \qquad (4)$$

where $\Delta W_{LS}(t)$ - power losses in the *LS* network.

- *DG*, *GN* – respectively, the diesel generator and the global (national) network to which ADHEC connects in exceptional situations, such as a) situation of shortage of power $W^{(+)}(t)$ in the ADHEC system, with the simultaneous discharge of the storage battery system, i.e. $x_{SB}(t) = x_{SB}^{min}$; b) situation of an excess of power $W_{GN}^{(-)}$ in the ADHEC system, with the storage battery system being charged to its maximum, i.e. $x_{SB}(t) = x_{SB}^{max}$.

- N_1, N_2 – nodes for connecting power lines.

- *CC* – the control center of the ADHEC system, designed to manage the energy balance therein, i.e. to manage the flows of power circulating in the ADHEC system.

2. The general outline of the method for the design of the optimal structure of ADHEC.

The design of the optimal structure of ADHEC includes the following stages and steps.

Stage 1. Research and creation of a database of statistical data on electrical loads of consumers $EC = \{EC_i \mid i \in N_{EC}\}$.

Step 1. Form a time series of power consumption based on observations (2) $\{W_{EC}(t) \mid t \in T\}$, where $T = \{t_0, t_1, ..., t_\tau\}$; t – discrete time; τ - discrete time number.

Step 2. Calculate the average power consumption $W_{EC\tau}$ and its standard deviation D_{EC}:

$$W_{EC\tau} = \frac{1}{\tau} \sum_{t \in T} W_{EC}(t); \qquad (5)$$

$$D_{EC} = \left(\frac{1}{\tau} \sum_{t \in T} (W_{EC}(t) - W_{EC\tau})^2 \right)^{\frac{1}{2}}; \qquad (6)$$

Stage 2. Research and creation of a statistical database of wind speed in the region under consideration (Fig. 2).

Step 3. Form a time series of wind speed based on observations $\{v_{h_0}(t) \mid t \in T\}$ for a given height (level) h_0 (for meteorological stations, it is assumed that h0 = 10 m) [22,23].

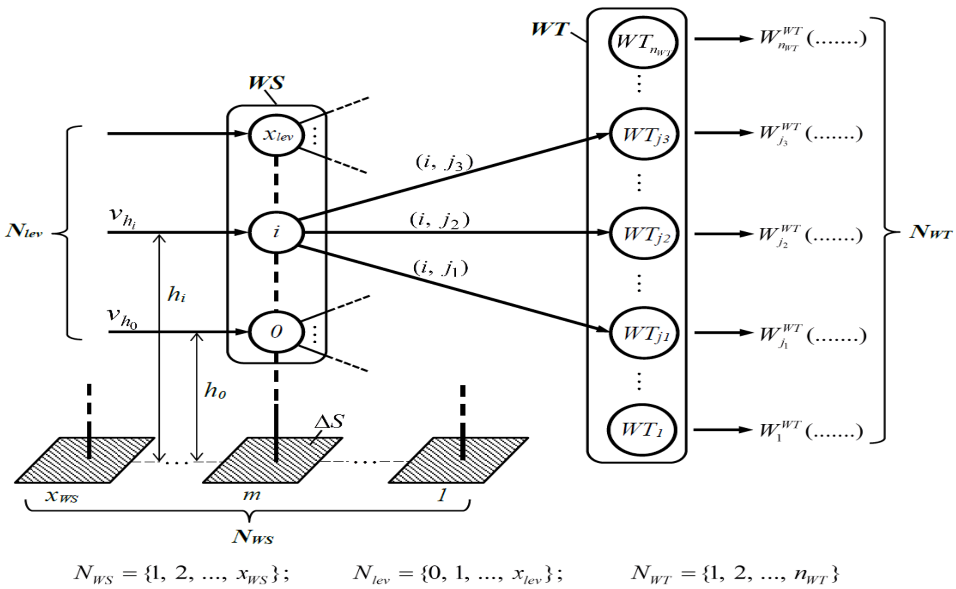

Fig. 2. The design of distributed systems of wind-powered generators (WPG)

Step 4. Calculate the average value of the wind speed $v_{h_0\tau}$ for the level h_0 and its standard deviation D_{h_0} :

$$v_{h_0\tau} = \frac{1}{\tau}\sum_{t\in T} v_{h_0}(t); \quad (7)$$

$$D_{h_0} = \left(\frac{1}{\tau}\sum_{t\in T}(v_{h_0}(t) - v_{h_0\tau})^2\right)^{1/2}; \quad (8)$$

Step 5. Calculate the average wind speed $v_{h_i\tau}$ for each level $h_i, i \in N_{yp} = \{1, 2, ..., n_{yp}\}$ based on the calculated average speed $v_{h_0\tau}$ (7) [22,23]:

$$v_{h_i\tau} = v_{h_0\tau} \cdot \left(\frac{h_i}{h_0}\right)^k; \quad (9)$$

where k – is an empirical indicator of the roughness of the underlying surface of the earth.

<u>*Stage 3*</u>. Research and creation of a statistical database of hydropower resources of mountain and lowland rivers.

The graph of a mountain river has a tree-like structure, the end nodes (river flows) of which are dispersed in the mountains at different heights (levels), and the root of the graph corresponds to the lowland part of the river (Fig. 3).

Step 6. In the graph, indicate the prospective sections of the rivers where hydroelectric units (HU) will be installed. Based on the observations, form a time series of water discharge $\{Q_i(t) |\ t \in T\}, \forall i \in N_{HG}$, air temperature $\{T_i^\circ(t) |\ t \in T\}, \forall i \in N_{HG}$, as well as a database of river fall for these sections. $J_i, \forall i \in N_{HG}$.

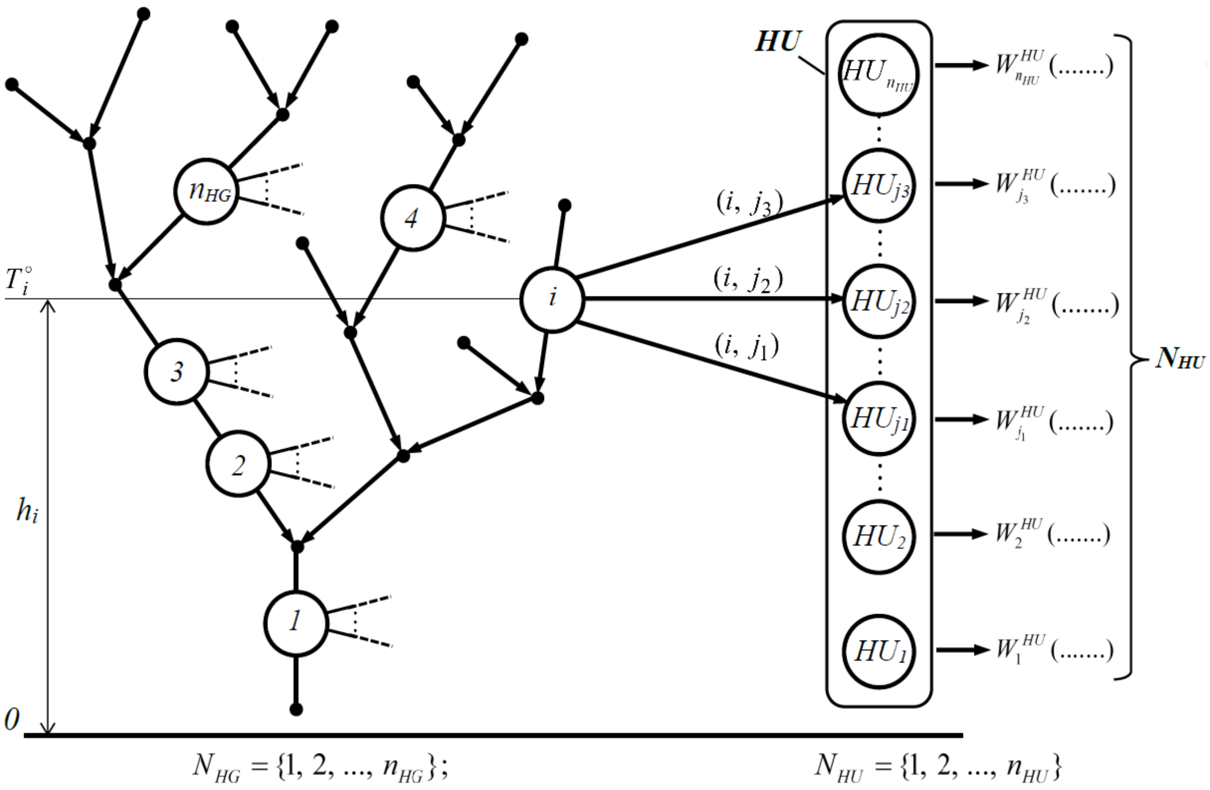

Fig. 3. The design of distributed systems of hydraulic generators (HG)

Step 7. Calculate the average value for each *i*-th section of the river $Q_{i\tau}$. Based on the aggregate (time series) $\{T_i^\circ(t) |\ t \in T_{win} \subset T\}$, where *Twin* corresponds to the winter season, calculate the powers $\{\Delta W_i^{HU}(t) |\ t \in T_{win}\}$ and distribute them over the time period τ :

$$\Delta W_{i\ \tau}^{HU} = \frac{1}{\tau}\sum_{t\in T_{win}} \Delta W_i^{HU}(t);$$

where $\{\Delta W_i^{HU}(t) |\ t \in T_{win}\}$ - power used for heating a lightweight construction to protect hydraulic units from freezing and preserve its operability during the winter season $T_{win} \subset T$.

<u>*Stage 4*</u>. Research and creation of a database of statistics on solar energy.

Step 8. Based on the observations, form a time series of power generated by one solar panel $\{W_{SC}^1(t) |\ t \in T\}$. (10)

Step 9. Calculate the average value of the generated power $W_{SC\tau}^1$ and its standard deviation: D_{SC}^1:

$$W_{SC\tau}^{1}=\frac{1}{\tau}\sum_{t\in T}W_{SC}^{1}\left(t\right); \qquad (11)$$

$$D_{SC}^{1}=\left(\frac{1}{\tau}\sum_{t\in T}(W_{SC}^{1}\left(t\right)-W_{SC\tau}^{1})^{2}\right)^{\frac{1}{2}}.$$

Stage 5. Research and development of a database of converters of wind and water energy into electrical energy (Fig.2).

Step 10. Form a set of wind turbines $WT=\left\{WT_j \mid j\in N_{WT}\right\}$, where each *j*-th unit WT_j represents a set composed of structurally compatible single converters of wind energy into electricity; $N_{WT}=\left\{1,2,...,n_{WT}\right\}$ - an aggregate of numbers of units; n_{WT} - the number of units. Note that a set can consist of one converter or a group of converters of the same or different types.

Step 11. Form a set of calculation formulas with one-to-one correspondence of each *j*-th formula to each *j*-th element of the set of wind turbine (WT) units:

$$\{W_j^{WT}\left(k_j,\eta,v_{hi\tau},S_{WT_j}\right)\mid j\in N_{WT}\}; \qquad (12)$$

where $W_j^{WT}\left(k_j,\eta,v_{hi\tau},S_{WT_j}\right)$ - the power of the *j*-th unit WT_j; k_j - unit efficiency; η - air density (under normal conditions $\eta=1,225$ kg / m³); $v_{hi\tau}$ - the average value of the wind speed for the level h_i, calculated using formulas (7)-(9); S_{WT_j} - the area of the wind flow of the unit WT_j.

According to [24], the formula from (12) is as follows:

$$W_j^{WT}\left(k_j,\eta,v_{hi\tau},S_{WT_j}\right)=\frac{k_j\cdot\eta\cdot\left(v_{hi\tau}\right)^{3}\cdot S_{WT_j}}{2}\ \text{[W]}; \qquad (13)$$

Stage 6. Research and development of a database of converters of water energy into electrical energy (Fig. 3).

Step 12. To form a set of hydraulic units $HU=\{HU_j\mid j\in N_{HU}\}$, where each *j*-th unit HU_j is a set made up of structurally compatible single converters of water energy into electricity; $N_{HU}=\left\{1,2,...,n_{HU}\right\}$ - an aggregate of the numbers of units; n_{HU} - the number of units. A set can consist of one converter or a group of converters of the same or different types.

Step 13. Form a set of calculation formulas with one-to-one correspondence of each *j*-th formula to each *j*-th element of the set of HU units:

$$\{W_j^{HU}\left(k_j,Q_j,H_j\right)\mid j\in N_{HU}\}; \qquad (14)$$

where $W_j^{HU}\left(k_j,Q_j,H_j\right)$ - the power of the *j*-th unit HU_j; k_j - unit efficiency; Q_j - water discharge of water flowing through the turbine; H - turbine head pressure.

According to [24], the formula from (14) is as follows:

$$W_j^{HU}\left(k_j,Q_j,H_j\right)=9810\cdot Q_j\cdot H_j\cdot k_j\ \text{[W]}; \qquad (15)$$

Stage 7. Development of efficient, from the point of view of structural and functional reliability and cost (self-sufficiency), autonomous distributed hybrid energy complexes and energy balance management systems.

The list of tasks to be solved at this stage is as follows:

- design of the optimal structure of the distributed hybrid generation system (DHGS) that ensures the required level of generated power W_G (1) at the minimal cost and with the required functional reliability;
- determine the total capacity C_{SB} of the SB system that will ensure the controllability of the energy balance in the AHDEC system at the minimal cost;
- design of the optimal structure of the local electrical network that will ensure the required level of structural and functional reliability, minimal power losses (4) ΔW_{LS} during its transportation and distribution to consumers, at the minimal cost;
- development of the ADHEC energy balance management system.

Note. The first task from the above list, i.e. the design of the optimal structure of the distributed hybrid generation system (DHGS), is addressed below; the remaining tasks lie outside the scope of this work.

3. Formal task definition for the design of a distributed hybrid generation system (DHGS).

Apparently, as the altitude increases, the wind speed increases, and so does the energy of the airflow. Therefore, each wind station (WS) should be made in the form of a tower, divided into levels (lev) by height (Fig. 2). The numbers of levels form an aggregate $N_{lev}=\left\{0,1,...,x_{lev}\right\}$, where x_{lev} is the number of levels; number 0 corresponds to the level of measurement of wind speed v_{h_0} at the meteorological station (7)-(9).

For each *i*-th level of the WS one single *j*-th unit WT_j is selected from the subset of alternative ones

$F_{WT}(i)$, elseways nothing is selected (here: $i \in N_{lev}$; $j \in F_{WT}(i) \subseteq N_{WT}$). For the example shown in Fig. 2, we get:

$$i \in N_{lev} = \{1, 2, ..., x_{WS}\};$$
$$j \in F_{WT}(i) = \{j_1, j_2, j_3\} \subseteq N_{WT} = \{1, 2, ..., n_{WT}\}.$$

For each i-th section of the river, one single j-th unit HU_j is selected from the subset of alternative ones $F_{HU}(i)$, elseways nothing is selected (here: $i \in N_{HG}$; $j \in F_{HU}(i) \subseteq N_{HU}$). For the example shown in Fig. 3, we get:

$$i \in N_{HG} = \{1, 2, ..., n_{HG}\};$$
$$j \in F_{HU}(i) = \{j_1, j_2, j_3\} \subseteq N_{HU} = \{1, 2, ..., n_{HU}\}.$$

Based on the above formulas (1) - (15) and illustrative figures 1, 2, 3, let us put down the formal definition of the task for the design of DHGS as follows:

***Target function J*:**

$$J = J_{WG} + J_{HG} + J_{SC}; \quad (16)$$

where $$J_{WG} = \left[\sum_{i=1}^{x_{lev}} \left(\sum_{j \in F_{WT}(i)} c_j^{WT} \cdot x_{ij}^{WT} \right) + c_{WS}\left(h_{x_{lev}}\right) + c_{\Delta S} \right] \cdot x_{WS}; \quad (17)$$

$$J_{HG} = \sum_{i \in N_{HG}} \sum_{j \in F_{HU}(i)} c_j^{HU} \cdot x_{ij}^{HU}; \quad (18)$$

$$J_{SC} = c_{SC} \cdot x_{SC}.$$

***System of limitations*:**

$$W_{WG} + W_{HG} + W_{SC} \geq W_{EC\tau}; \quad (19)$$

$$W_{WG} = \left[\sum_{i=1}^{x_{lev}} \sum_{j \in F_{WT}(i)} \left(W_j^{WT}\left(k_j, \eta, v_{hi\tau}, S_j^{WT}\right) - \Delta W_j^{WT} \right) \cdot x_{ij}^{WT} \right] \cdot x_{WS}; \quad (20)$$

$$W_{HG} = \sum_{i \in N_{HG}} \left[\left(\sum_{j \in F_{HU}(i)} W_j^{HU}\left(k_j, Q_j, H_j\right) \cdot x_{ij}^{HU} \right) - \Delta W_{i\ \tau}^{HU} \right]; \quad (21)$$

$$W_{SC} = W_{SC\tau}^{1} \cdot x_{SC}; \quad (22)$$

$$\left(\sum_{j \in F_{WT}(i)} x_{ij}^{WT} \right) \in \{0,1\}, \forall i \in N_{lev} = \{1, 2, ..., x_{lev}\}; \quad (23)$$

$$\left(\sum_{j \in F_{HU}(i)} x_{ij}^{HU} \right) \in \{0,1\}, \forall i \in N_{HG} = \{1, 2, ..., n_{HG}\}. \quad (24)$$

$$\begin{cases} x_{lev} \in N = \{1, 2, ...\}, \\ x_{WS} \in N = \{1, 2, ...\}, \\ x_{SC} \in N = \{1, 2, ...\}, \\ x_{ij}^{WT} \in \{0,1\}, \forall j \in F_{WT}(i), \forall i \in N_{lev} = \{1, 2, ..., x_{lev}\}, \\ x_{ij}^{HU} \in \{0,1\}, \forall j \in F_{HU}(i), \forall i \in N_{HG} = \{1, 2, ..., n_{HG}\}. \end{cases} \quad (25)$$

***The unknowns*:**

$$x_{lev}, x_{WS}, x_{SC}, \{x_{ij}^{WT} \mid j \in \Gamma_{WT}(i), i \in N_{lev}\}, \{x_{ij}^{HU} \mid j \in F_{HU}(i), i \in N_{HG}\}. \quad (26)$$

The task for the design of a distributed hybrid generation system (DHGS)

The task is to find the values of the unknowns (26) that would comply with the system of limitations (19) - (25) and would ensure the minimal value of the target function (16), i.e. the following optimization task should be solved:

$$\min_{\substack{by\ variables \\ from(26)}} \{J \mid with\, restrictions\,(19)-(25)\}; \quad (27)$$

The symbols here stand for the following:

- J – target function - the cost of the designed distributed hybrid generation system (DHGS) ;

- J_{WG}, J_{HG}, J_{SC} - the cost of a distributed system, namely the wind generators WG, hydraulic generators HG, solar cells SC, respectively (16) - (18);

- c_j^{WT} - the cost of the $j \in F_{WT}(i)$ - th unit WT_j with the number j out of the subset of alternative numbers $F_{WT}(i)$ that corresponds to the $i \in N_{lev}$ -th module (level) of the WS (see Fig. 2);

- $x_{ij}^{WT} \in \{0,1\}$ - defines: if $x_{ij}^{WT} = 1$, then choose the unit WT_j for the i-th module; otherwise (i.e., at $x_{ij}^{WT} = 0$) – discard (x_{ij}^{WT} - unknown entity);

- $c_{WS}\left(h_{x_{lev}}\right)$ - the cost of the WS station tower, depending on the height of the $h_{x_{lev}}$ $i = x_{lev}$ - th level (see Fig. 2);

- $c_{\Delta S}$ - the cost of the area ΔS occupied by the WS station (see Fig. 2);

- x_{WS} - number of WS stations (unknown entity);

- c_j^{HU} - the cost of the $j \in F_{HU}(i)$ -th unit HU_j with number j from the subset of alternative numbers $F_{HU}(i)$, corresponding $i \in N_{HG}$ - th section of the river (see Fig. 3);

- $x_{ij}^{HU} \in \{0,1\}$ - defines: if $x_{ij}^{HU} = 1$, then choose the unit HU_j, for the i-th section of the river, otherwise (that is, at $x_{ij}^{HU} = 0$) – discard (x_{ij}^{HU} - unknown entity);

- c_{SC} - cost of one solar panel system SC;

- x_{SC} - number of SC system panels (unknown entity);

- statement (19) shows the requirements for the total generated power of the distributed hybrid system DHGS, consisting of WG, HG, SC (see (1) - (15) and Figures 1, 2, 3);

- statements (20) - (22) show the power generated by WG, HG, SC systems, respectively; $\Delta W_j^{WT}, \Delta W_i^{HU}$ - power for auxiliary needs of the WT_j, HU_i units, respectively (see (1) - (15) and Figures 1, 2, 3);

- statement $\left(\sum_{j \in F_{WT}(i)} x_{ij}^{WT}\right) \in \{0,1\}$ from (23) – defines if at least one unit WT_j with number j from the subset of alternative numbers is installed in the i-th WS module $F_{WT}(i)$;

- statement $\left(\sum_{j \in F_{HU}(i)} x_{ij}^{HU}\right) \in \{0,1\}$ from (24) – defines if at least one unit HU_j with number j from the subset of alternative numbers is installed in the i-th section of the river $F_{HU}(i)$.

Conclusion

The paper covers the following issues: data research and creation of a statistical database of electric loads of consumers, of the wind speed in the region under consideration, of the hydroelectric potential of mountain and lowland rivers, of the solar energy, as well as research and development of a database of converters of wind and water energy into electrical energy. The paper addresses the task of designing the optimal structure of the distributed hybrid generation system that will ensure the required power generation level at a minimal cost and with necessary functional reliability.

The paper provides a general outline of the method for the design of the optimal structure of autonomous distributed hybrid energy complexes and control of the energy balance therein.

The mathematical apparatus suggested for the henceforth development of the ADHEC CAD system is the mathematical apparatus of computational Petri nets (CPN) [18,19], which is an extension of the classical theory of Petri nets [20, 21].

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