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MODEL OF THE ELECTRIC NETWORK BASED ON THE FRACTAL-CLUSTER PRINCIPLE

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Abstract. *Energy systems with a significant share of distributed generation in modern energy play an increasingly important role and contribute to the green transition. In the Ukrainian energy sector, the introduction of distributed generation also occurs under conditions of military influence on energy infrastructure facilities, which additionally forces the distribution of generation facilities across the territory of the respective regions of the country. The fundamental difference between distributed generation systems and traditional power systems with concentrated generating capacities is the consumption of energy at the place of its generation. This sets the task of reviewing the general principles of building the configuration of electrical networks. The idealized model of the branched electrical network of the power system with distributed generation is proposed in the work, which takes into account the features of systems with distributed generation. This model is based on the fractal-cluster principle of forming the configuration of electrical networks. It is proposed to build an electrical distribution network based on a regular fractal. The assumptions and limitations of the model are defined. Modeling of the structure and configuration of electrical networks was carried out. The electrical power of the underlying network cluster is determined. The basic fractal properties of the proposed idealized distribution network model are determined. Circuit solutions of unified node substations and basic network cluster are proposed.*

Keywords: distributed generation, fractal-cluster principle, electrical networks, unified substation circuits, determination of optimum voltage, configuration of electrical networks

MODEL SIECI ENERGETYCZNEJ OPARTY NA ZASADZIE FRAKTALNO-KLASTROWEJ

Streszczenie. *Systemy energetyczne ze znacznym udziałem generacji rozproszonej w nowoczesnej energetyce odgrywają coraz ważniejszą rolę i przyczyniają się do zielonej transformacji. W ukraińskim sektorze energetycznym wprowadzenie generacji rozproszonej odbywa się również w warunkach wpływu wojskowego na obiekty infrastruktury energetycznej, co dodatkowo wymusza rozmieszczenie obiektów wytwórczych na terytorium poszczególnych regionów kraju. Podstawową różnicą między systemami generacji rozproszonej a tradycyjnymi systemami energetycznymi o skoncentrowanych mocach wytwórczych jest zużycie energii w miejscu jej wytwarzania. Stawia to przed nami zadanie przeglądu ogólnych zasad budowy konfiguracji sieci elektroenergetycznych. W pracy zaproponowano wyidealizowany model rozgałęzionej sieci elektroenergetycznej z generacją rozproszoną, który uwzględnia cechy systemów z generacją rozproszoną. Model ten opiera się na fraktalno-klastrowej zasadzie tworzenia konfiguracji sieci elektrycznych. Zaproponowano budowę elektrycznej sieci dystrybucyjnej w oparciu o regularny fraktal. Określono założenia i ograniczenia modelu. Przeprowadzono modelowanie struktury i konfiguracji sieci elektrycznych. Określono moc elektryczną podstawowego klastra sieci. Określono podstawowe właściwości fraktalne proponowanego wyidealizowanego modelu sieci dystrybucyjnej. Zaproponowano rozwiązania obwodowe zunifikowanych podstacji węzłowych i podstawowego klastra sieciowego.*

Słowa kluczowe: wytwarzanie rozproszone, zasada klastra fraktalnego, sieci elektryczne, ujednolicone obwody podstacji, określenie napięcia optymalnego, konfiguracja sieci elektrycznych

Introduction

The existing structure of electric networks of Ukraine is multi-level, hierarchical, branched [4, 11]. It is formed on the basis of the general principle of centralization, concentration and enlargement of production capacities. Currently, the capacity of the main aggregates of Ukrainian power plants and substations and the capacity of power lines are in line from tens to hundreds of megawatts, and the largest generators of nuclear power plants reach a new capacity of 1000 MW. Given this, the Ukrainian electricity system can be considered centralized and uneven with the presence of concentrated nodes for generating and transmitting electricity. It was this structure that proved unstable to external influences of a military nature. During the period of the aggressor's invasion of Ukraine, there were several periods of failures in the work of the united energy system of Ukraine on a national scale [14, 20]. Destruction of critical objects of Ukrainian energy is a real-achievable goal of the enemy, which will lead to catastrophic consequences and paralysis of all spheres of production and civil life of citizens [29].

In view of this, the issue of developing new principles for constructing the configuration of electrical networks becomes relevant, which will significantly increase the stability of the operation of electrical networks and increase the level of energy security of all its facilities. To do this, it is necessary to develop new principles for the construction of branched electrical networks, which will significantly increase the stability of their functioning even in conditions of hostilities [1, 13, 22].

Consequently, the purpose of this work is to develop general approaches to the design of the configuration of electrical networks and the development of an idealized model of electrical networks with increased resistance to military influences [28].

1. General approach. Define model assumptions and constraints

For the initial modern conditions of operation of the electrical networks of Ukraine, we accept the possibility of their destruction during directed rocket attacks and by means of unmanned aerial vehicles, as well as through sabotage by the aggressor.

At the same time, we consider these means of destruction limited in the number of applications, taking into account the available capabilities of the enemy and the effective work of the defense forces of Ukraine [2, 30].

Proceeding from this, one of the effective means of counteracting the purposeful attempts to destroy the Ukrainian energy sector is the application of the principles of dispersion and decentralization in power supply systems. This will lead to grinding and a corresponding increase in the number of targets for the enemy, which will increase by orders of magnitude and make meaningless his attempts to de-energize large regions of the country and the state as a whole [19, 26].

In addition to the development of distributed generation systems, we are encouraged by general trends in the development of technologies and society such as:

- individualization of production, services and social structures;
- development of alternative autonomous energy sources;
- development of control systems and automation of the power supply process;
- continuation of the trend towards energy efficient consumption of energy resources [3, 9].

Characteristic sources of energy in networks with distributed generation are usually sources of power which are called alternative. For the conditions of Ukraine, the most inherent power sources in distributed generation systems are solar photovoltaic power plants, wind power plants, biogas power plants and mini and micro hydroelectric power plants.

According to the principles of distributed generation of the product, electric energy is consumed as close as possible to the place of its generation, and regional distribution and system-forming networks perform the function of redirecting the flows of excess energy from one part of the system to another [10]. Thus, high-voltage networks become more unloaded and do not play the role of the main power source and the main energy corridor, because they circulate only the imbalance energy between individual parts of the combined energy system [17, 25].

Due to the fact that the generation of electricity in systems with distributed generation is a large number of low-power sources that are located in the country (region), the basic element of the generation system is not a point on the map, but the area of a certain site, which has its own energy potential. This potential may be sufficient, insufficient or excessive [12, 31]. Accordingly, this elementary base section will play the role of either a neutral transit link of the network, or a consumer, or an energy source. At the same time, for each specific section, this role can change over time in accordance with the change in the mode of generation-consumption of electric energy [21].

In systems with distributed generation, the main function of electrical networks is not the transfer of large amounts of energy itself, but the reliable connection of all elements of the network [24]. Therefore, the requirements for operational flexibility and redundancy of power lines (communications) come to the fore.

Thus, we determine the basic initial conditions for further modelling of the structure and configuration of distribution electrical networks with distributed generation by electricity consumption.

1. Sources of electric energy generation and its consumers of the area under consideration have a character distributed over the area.
2. The installed capacity of energy sources of each section of the area has a value which, under favourable generation conditions, meets or exceeds the needs of electric energy consumers of this section.
3. The mode of generation of energy sources of each site implies a certain lack of energy under adverse generation conditions.
4. The operation mode of the electrical equipment of each section or several sections may be disrupted due to military intervention or as a result of other emergency situations of weather-climatic and operational-technical nature.
5. In the area under consideration there are no high-power (concentrated) consumers of electric energy and its sources.
6. At the modelling stage, we assume that all power lines are made with a wire of the same brand and intersection.

2. Modelling the configuration of electrical networks of the distributed generation system

The paper proposes to consider the fractal-cluster principle of construction of electrical networks in systems with distributed generation [5, 8].

Fractal-cluster structures are characteristic of many both natural and technological glass-bottom systems and processes [6, 7, 18].

It is known that modern electrical networks have fractal properties of irregular fractal that affect their characteristics and technological environment [16, 18].

The task of the fractal-cluster structure of the electrical network proposed in this work is:

- ensuring high reliability and stability of the network to external influences of military and terrorist characters;
- unification of technological solutions and network elements;
- high operational flexibility and simple logic of operational switching in normal and abnormal operating modes.

The paper proposes one of the possible structures of fractal-cluster networks, which is shown in Fig. 1.

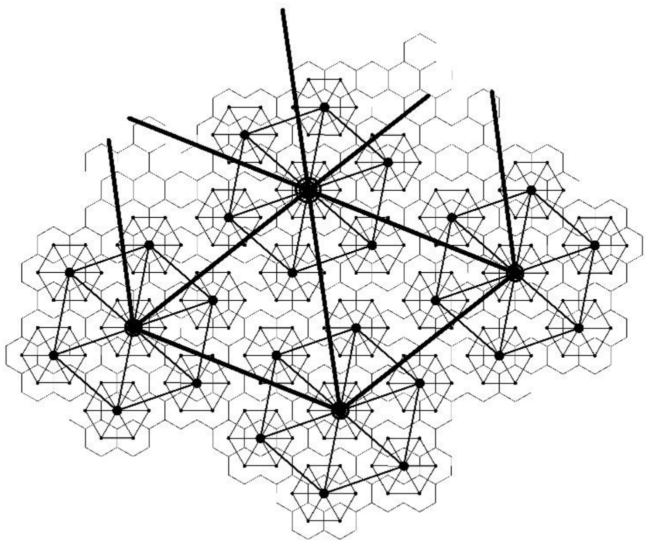
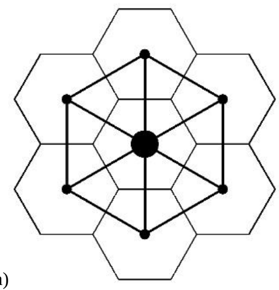
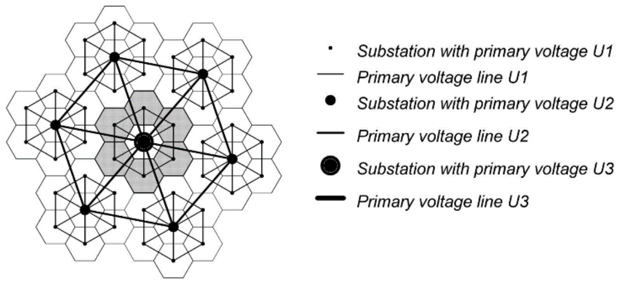


Fig. 1. Fragment of branched fractal-cluster structure of electric networks with distributed generation

It is proposed to choose an area that is bounded by a hexagon for the base area. This is due to the well-known property of honeycomb structures in which there is an optimal relationship between the area of the figure and the length of its perimeter [15, 29]. This property will greatly optimize the consumption of conductive material to create a specified network.



a)



b)

Fig. 2. Fractal-cluster structure of electrical networks with distributed generation: a) basic cluster of network structure, b) principle of formation of multilevel fractal-cluster structure

For the basic cluster of the fractal-cluster structure (Fig. 2a) in our case, we take the structure, which consists of the seventh sections of the area of the hexagonal form area that have a point of connection (delivery-reception of electric energy) that is located in the center of the figure and in the real situation performs the functions of a switchgear [23]. The switchgears of the six sections bordering the cluster boundary are connected to each other in a circular pattern and are radially connected to the switchgear of the central (seventh) section. In the center of the seventh section there is also a substation that provides communication between the electrical network of the base cluster with voltage U_1 and the networks of higher voltage U_2 that form the fractal of the next iteration and so on (Fig. 2b).

2.1. Determine the electrical power of the underlying network cluster

The scheme of replacement of the electrical network of the base cluster is shown in Fig. 3. It has seven nodes which are characterized by the value of electric power expressed in complex form $P + jQ$ which varies over time and can have both positive (generation) and negative (consumption) values. Considering that under the conditions of modelling all the wires of the cluster network are made with a wire of the same brand and the intersection in the future we replace the resistance parameters with the parameters of the lengths of the sections of the electric transmission lines [27]. Determine in general terms the flow distribution by the cluster network and its total power at the point of attachment to the cluster of the next iteration.

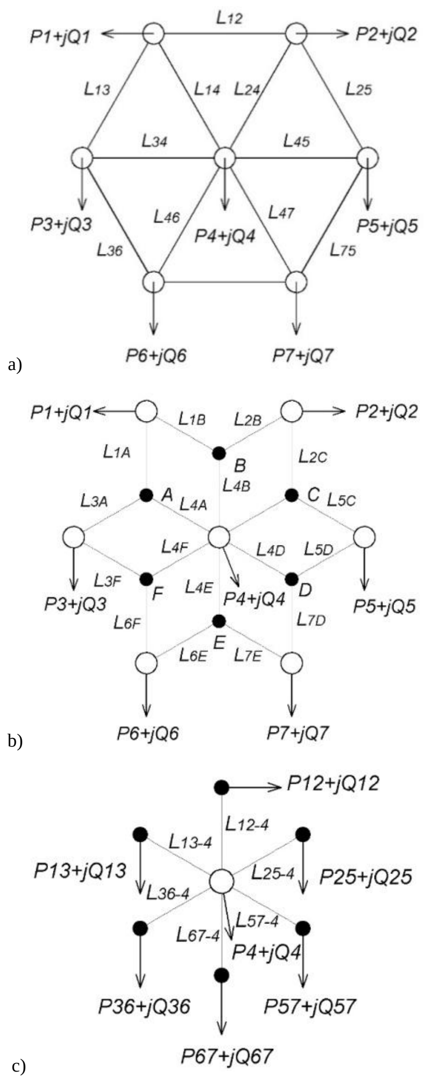


Fig. 3. Calculated transformation of the underlying network cluster

To do this, we will carry out a sequential transformation of the network replacement schema of the base cluster. At the first stage, we transform the "triangles" between the nodes of powers into equivalent "stars" using the example of triangle 1-3-4 according to the formulas (1), its sides L_{13}, L_{14}, L_{34} (Fig. 3a) are transformed into rays of the "stars" L_{1A}, L_{3A}, L_{4A} (Fig. 3b).

$$L_{1A} = \frac{L_{13} \cdot L_{14}}{L_{13} + L_{14} + L_{34}}$$
$$L_{3A} = \frac{L_{13} \cdot L_{34}}{L_{13} + L_{14} + L_{34}} \qquad (1)$$
$$L_{4A} = \frac{L_{14} \cdot L_{34}}{L_{13} + L_{14} + L_{34}}$$

Given that the length of all the lines of the base cluster is the same, it can be taken as a base value and calculated in general in relative units. In this case, we get that all equivalent supports of the lines of the second stage of the transformation are also the same and three times less than the equivalent resistance value, and instead of twelve sections, the equivalent scheme has eighteen sections [12, 18].

In the next step of the transformation, we will spread the powers of nodes 1–7 along the adjacent formed virtua-line nodes A, B, C, D, E, F (centers of the "stars"). Diversity is performed by the method of reverse arms. Given that the equivalent length of all lines of the second stage of the base cluster transformation is the same, the powers of the nodes are divided in half and spread to neighbouring nodes.

$$S_{13} = \frac{1}{2}(P_1 + P_3) + j\frac{1}{2}(Q_1 + Q_3)$$
$$S_{12} = \frac{1}{2}(P_1 + P_2) + j\frac{1}{2}(Q_1 + Q_2)$$
$$S_{25} = \frac{1}{2}(P_2 + P_5) + j\frac{1}{2}(Q_2 + Q_5)$$
$$S_{57} = \frac{1}{2}(P_5 + P_7) + j\frac{1}{2}(Q_5 + Q_7) \qquad (2)$$
$$S_{67} = \frac{1}{2}(P_6 + P_7) + j\frac{1}{2}(Q_6 + Q_7)$$
$$S_{36} = \frac{1}{2}(P_3 + P_6) + j\frac{1}{2}(Q_3 + Q_6)$$

As a result of transformations, we get a six-pointed equivalent star (Fig. 3b), the total power balance of which is found according to Kirchhoff's first law, that is, due to the algebraic addition of all equivalent powers in node 4 (3).

$$S_{\Sigma} = \sum_{n=7}^{1} P + j\sum_{n=7}^{1} Q \qquad (3)$$

Given that in (2) all the active and reactive components of the powers of nodes 1–6, bisected by two, we can say that the total power balance of the base cluster of the network is equal to the algebraic sum of the powers of all nodes. Such a simple calculation algorithm is due to the symmetric network configuration of the underlying cluster and is stored at all levels of fractal iteration [3, 11].

2.2. Defining the fractal properties of an idealized distribution network model

The proposed configuration of an idealized distribution network model has the character of a regular fractal like the Serpinsky napkin or Koch snowflake. Determine the basic relations of the geometry of the space of this fractal.

First of all, we determine the basic coefficient of increasing the length of power lines when switching from a fractal of a smaller iteration to a fractal of a larger iteration (Fig. 4).

In the proposed network structure, the hexagon of the electrified area with the length of side a_1 and the corresponding area S_1, which is defined as:

$$S_1 = \frac{3a_1^2\sqrt{3}}{2} \tag{4}$$

In this case, the unified length of the fractal power line of the first iteration L_1 is equal to two heights of the ABC triangle (as an element of the basic hexagon with side a_1) and is equal to

$$L_1 = 2\frac{a_1\sqrt{3}}{2} = a_1 \cdot \sqrt{3} \tag{5}$$

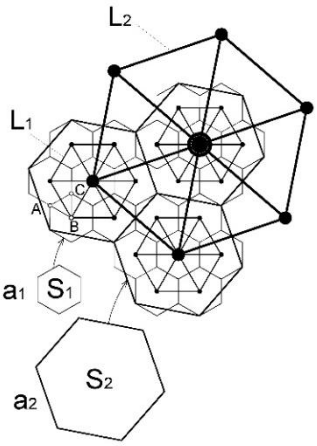


Fig. 4. Determination of geometric relations of fractal network structure

When moving to the fractal of the second iteration, the elementary base of the area becomes a hexagon with side a_2 and area S_2 which is equal to

$$S_2 = 7S_1 \tag{6}$$

since the elementary basis of the fractal area of the second iteration covers seven elementary bases of the area of the previous fractal of the first iteration (Fig. 5).

Knowing the area S_2 similarly to formula (4) one can derive the value for side a_2 expressed in terms of a_1 and S_1 as

$$a_2 = \sqrt{\frac{2}{3\sqrt{3}}7S_1} = \sqrt{\frac{2}{3\sqrt{3}}7\frac{3a_1^2\sqrt{3}}{2}} = \sqrt{7} \cdot a_1 \tag{7}$$

where in similar to formula (5)

$$L_2 = 2\frac{a_2\sqrt{3}}{2} = a_2 \cdot \sqrt{3} \tag{8}$$

and assuming that $a_2 = \sqrt{7} \cdot a_1$ we define a similar relationship between L_1 and L_2 as $L_2 = \sqrt{7} \cdot L_1$.

Thus, the indicator $\sqrt{7}$ is the natural scale of the fractal structure of the electrical network under consideration. It reflects the basic character properties of fractals such as self-similarity and scale invariance. Each subsequent iteration of this fractal increases the length of unified power lines in $\sqrt{7}$ times.

Determine the total length of power lines for each iteration of the fractal. It is obvious that the total length of the transmission lines of the base cluster of the first iteration of voltage U_1 is $12L_1$ or $12\sqrt{3}a_1$.

This line length forms the primary low voltage distribution network U_1 in the area of the base cluster area. At the second stage of iteration, the cluster area increases by 7 times, and accordingly the total length of low-voltage power lines with voltage U_1 of seven base clusters, which form the total area of the cluster area of the second iteration, will increase by 7 times.

In this case, a network of voltage U_2 appears, which forms a network of the cluster of the second iteration similar to the network of the base cluster. Its length is defined as $12L_2$ or $12\sqrt{3}a_2$ or $12\sqrt{3}\sqrt{7}a_1$ or $12\sqrt{21}\,a_1$.

The total length of the distribution networks of voltage U_1 and U_2 together with the cluster of the second iteration of the fractal in question will be equal to:

$$7 \times 12\sqrt{3}\cdot a_1 + 12\sqrt{21}\cdot a_1 \tag{9}$$

and for fractal of the third iteration:

$$7\times(7\times12\sqrt{3}\cdot a_1 + 12\sqrt{21}\cdot a_1) + 12\sqrt{147}\cdot a_1 \tag{10}$$

and so on.

That is, if the total length of the power lines of the fractal of each iteration is determined as $\sum L_i$, then in a generalized form the formula for calculating the total length of electrical networks that are built according to the fractal-cluster principle and the specified structure will have the form:

$$\sum L_{i=n} = 7\sum L_{i=n-1} + 12L_n \tag{11}$$

The specific length of power lines of the network relative to the area of the district is defined as:

$$L_{num} = \frac{\sum L_{i=n}}{S_n} \tag{12}$$

where S_n is the area of the fractal iteration network n, km^2.

So, it can conclude that:

1. The basic element for further constructing the configuration of this idealized model is the regular hexagon of the hexagon of the area of the electrified area with side a_1. It is used as the basis of the form of clusters of all iterations. Because of its linear size, all other linear dimensions of a given fractal structure can be calculated.
2. The natural spatial scale of the fractal considered by increasing linear dimensions is magnitude $\sqrt{7}$, and by increasing the area is scale 7.
3. As the number of fractal iterations increases, the complexity of space increases nonlinearly, which affects the change in the fractal dimension of this structure.

Obviously, with each subsequent iteration of the fractal network, its spatial complexity will increase due to the addition of elements of power lines more and more voltage, and accordingly the specific length of power lines will increase. However, the degree of this growth with each subsequent iteration will decrease. This is clearly seen in the results of calculations (table 1).

2.3. Determination of nomenclature of rated voltages of electrical distribution networks by level of iteration

The proposed model of the electrical network has several iterations. In this case, each iteration of the fractal must have its own nominal voltage. The rated voltage of electrical networks depends on the power transmitted by the power line and the distance to which the specified power must be transmitted. There are several methods for determining the possible rated voltages of electrical networks. In this work we will use the empirical calculation formula according to which the optimal voltage is:

$$U_{opt} = \frac{1000}{\sqrt{500/L + 2500/P}} \tag{13}$$

where L – length of unified line [km], P – transferred active power [MW].

The use of this (calculation) method of determining the rated voltage for network fractal iterations is due to the idealization of the model and the theoretical nature of the study.

The linear dimensions of the sections of the L network are calculated as given above, and the transmitted active power is calculated according to the specific parameter P_{spec} (MW/km^2). In this paper, we take this indicator as the average value of the power generated by Ukrainian power plants of all types in 2013 (194,377 million kWh) reduced to the area of the country (603,628 km^2) and with the value of the number of hours of use of the maximum installed power of 84,560 hours (i.e. virtual 100% load per unit area). So:

$$P_{num} = \frac{194377}{8760 \cdot 603628} = 0.0368 \ \text{MW/km}^2 \qquad (14)$$

Such data will reflect the natural mode of operation of the economy and, accordingly, the energy of Ukraine on the eve of military aggression by the aggressor country. Thus, the work simulates the mode of maximum load of distribution electric networks operating in the mode of transmitting the full power of consumers/generators from/to the power cluster, although in fact in networks with distributed generation the generated electric energy is consumed mainly at the place of its generation, and mainly imbalance flows fall into the distribution network. Based on this, the determined values will simulate the most intense mode of operation of the simulated electrical network.

2.4. Idealized model metrics calculation

Results of idealized model metrics calculation are given in table 1 and figure 5.

Table 1 shows the results of calculating the indicators of the idealized model of the electric network of the fractal-cluster type for nine iterations of the fractal of the base cluster with the side a_1 of the elementary hexagon, which is 1 km. At the sixth stage of the iteration, the area of the S_{kl} cluster becomes bearing with the territory of Ukraine, and at the seventh stage it already exceeds it. Therefore, for practical calculations, these positions are marginal in their feasibility, but the calculation of the eighth and ninth degrees of iteration gives an understanding of the general dynamics of the change in the specific length of L_{spec} power lines, which after the seventh iteration does not change much, which indicates the non-linear nature of the change in the complexity of space, which is characteristic of fractal structures. This dependence is shown in Figure 5. Dependencies are constructed for fractals with different primary geometric dimensions of an elemental base hexagon with a side from 1 to 10 km. At large primary linear dimensions of an elementary hexagon, the specific length of power lines almost remains unchanged depending on the scale of the fractal and the number of its iteration.

The specific length of power transmission lines to the electricity distribution operator in the Kharkiv region of JSC Kharkivoblenergo was 40,419 km of overhead power transmission lines and 6095 km of cable lines. At the same time, the area of the Kharkov region is 31.4 thousand km^2. That is, at voltage ratings from 6 to 110 kV, the specific length of the electric radio lines of the existing electrical networks of the Kharkov region is at least 1.48 km/km^2. Thus, the specific length of power lines when implementing the proposed idealized model will not increase significantly. And given that all power lines in this model are single-stranded, it almost does not change.

As for the optimal stresses of the characteristic fractal iterations, they, according to calculations, have seven recommended steps from 6 kV to 970 kV, which is technically possible for implementation. Table 2 shows the calculated data of the corresponding calculations for the fractal-cluster structure of the electrical network with different primary geometric dimensions of an elementary base hexagon with a side from 1 to 10 km.

The table shows that with an increase in the linear dimensions of the base hexagon, the number of network fractal iterations will decrease due to the inexpediency of technical implementation for reasons such as ultra-high voltages (over 1000 kV) and insufficient network density and branching. The closest approximate version of the line of rated voltages of the proposed network model to the existing line of rated voltages of high-voltage networks of Ukraine are options with linear dimensions of the side of the base hexagon of 1.2 and 3 km.

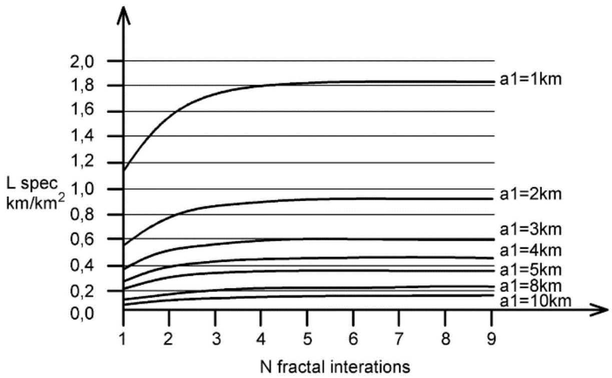


Fig. 5. Nonlinear nature of the change in the complexity of space, which is characteristic of fractal structures

Table 1. Idealized model results

N fractal iterations	P_{spec}	a	S_{el}	S_{kl}	L_1	P	U_{opt}	*Summa L*	L_{spec}
	MW/km^2	km	km^2	km^2	km	MW	kV	km	km/km^2
1	0.0368	1.00	2.60	18.17	1.73	0.10	6.15	20.76	1.1429
2	0.0368	2.65	18.17	127.18	4.58	0.67	16.12	200.25	1.5746
3	0.0368	7.00	127.20	890.42	12.11	4.68	41.69	1547.10	1.7375
4	0.0368	18.53	890.59	6234.11	32.05	32.77	104.32	11212.32	1.7989
5	0.0368	49.02	6235.28	43646.97	84.80	229.46	244.04	79517.84	1.8218
6	0.0368	129.70	43655.18	305586.24	224.39	1606.51	514.04	559317.53	1.8303
7	0.0368	343.19	305643.69	2139505.9	593.72	11247.69	969.27	3922347.44	1.8333
8	0.0368	908.09	2139908.1	14979356	1571.00	78748.62	1690.27	27475284	1.8342
9	0.0368	2409.81	14982172	104875209	4156.85	551343.96	2830.49	192376870	1.8343

Table 2. Optimal voltages of networks of different iterations

N fractal iterations	a_1, km						
	1	2	3	4	5	8	10
	U_{opt}, kV						
1	6.15	12.13	18.24	24.19	30.08	47.40	58.65
2	16.12	31.79	47.07	61.90	76.38	117.79	143.87
3	41.69	80.54	116.96	151.27	183.75	272.12	324.98
4	104.32	192.91	270.41	339.66	402.54	564.15	656.12
5	244.04	419.89	561.13	681.21	786.88	1049.87	1196.46
6	514.04	815.63	1045.03	1236.23	1403.16	1817.12	2048.11
7	969.27	1448.46	1809.50	2110.87	2374.77	3032.52	3401.35
8	1690.27	2446.52	3020.37	3501.74	3924.62	4982.61	5577.60
9	2830.49	4039.78	4963.02	5739.72	6423.20	8136.20	9100.82

2.5. Development of circuit solutions for the electrical network

Operational flexibility and reliability of the electrical network is determined primarily by the introduced circuit solutions. In the network configuration proposed above, it is possible to apply a single unified substation scheme with three power line connections and two power transformer connections (Fig. 6). Such a scheme will allow the implementation of a configuration with a ring transit connection of circuit substations and their connection to the central substation of the cluster. The proposed scheme uses four high-voltage switches for five connections, which is a fairly economical option.

Compared to a typical bridge substation scheme, only one switch is added per additional connection. This scheme is typical for 330–750 kV switchgears that are assembled according to the "3/2" or "4/3" scheme. Like these schemes, the proposed scheme has a simple and understandable algorithm of operational switching. Each connection is protected at once by two switches that provide high selectivity of protection and localize any accident only in the area where it occurred. Also, the repair of any part of the substation circuit is carried out according to the same switching algorithm, which reduces the likelihood of erroneous actions of operating personnel and accelerates the response time to changes in standard operating modes and in emergency modes. Also, the connection of the substation along the three lines to a large extent under-protects the reliability of its operation.

Fig. 7 shows the electrical schematic diagram of the connections of the substations of the base cluster of the mayor, which is modeled in operation. In accordance with it, the me-mode of the base cluster has six unified substations *PS1 – PS6* with voltages U_1 and U_2 assembled according to the scheme from Fig. 3 and a node substation *PS7* which has three voltage levels (U_1, U_2, U_3) and provides the connection of the base cluster with the fractal of the next iteration with a higher voltage level U_3. At the same time, part of the node substation *PS7* voltage from U_1 to U_2 is made according to the scheme "two blocks with a strap-on jumper," which simplifies and reduces the cost of this part, and the high-voltage switchgear U_3 is made according to the unified scheme of Fig. 6 which is proposed in this work. This switchgear is already a fractal element of the next iteration and repeats circuit solutions at a higher voltage level. This self-similarity is characteristic of fractal structures.

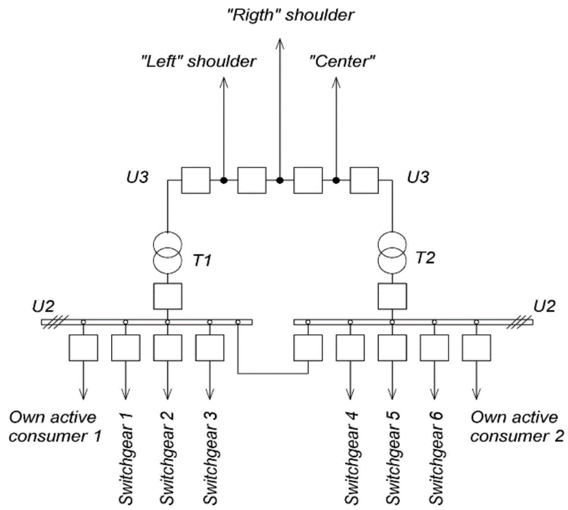


Fig. 6. Scheme of primary connections of unified substation

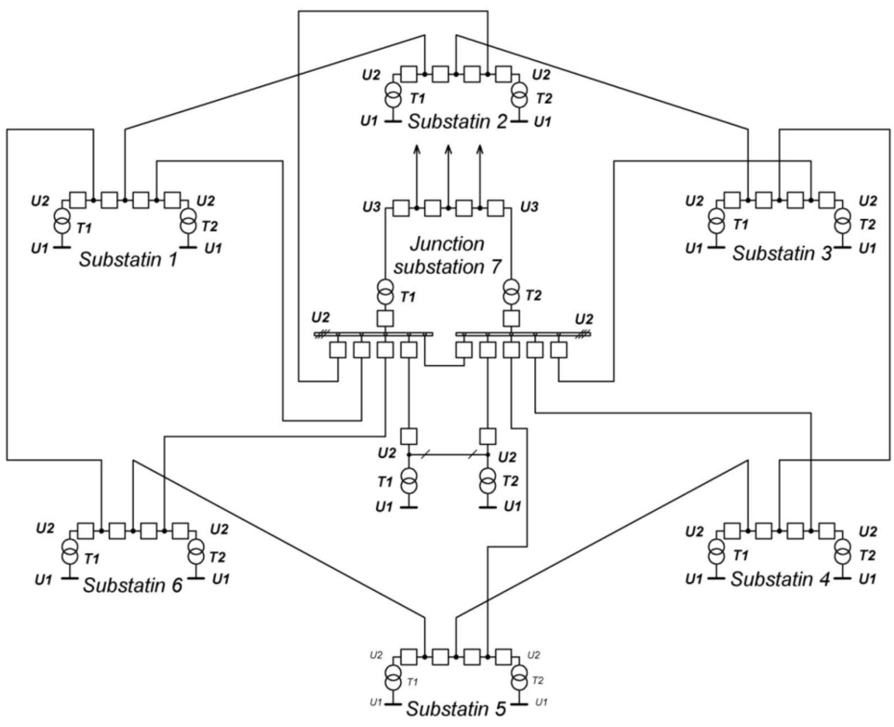


Fig. 7. Schematic of the basic cluster's framework

The proposed model of the electrical network is idealized and is intended for further adaptation to real conditions. This adaptation is supposed to be carried out by reconstructing existing electrical networks in such a way that they acquire fractal features and advantages of an idealized model.

The given idealized model reflects the general principles of constructing the configuration of electrical networks that can be implemented for the widest range of parameters of elements of electrical networks such as loads, the amount of electrical energy generation, the length of power lines, the intersection of wires, etc.

2.6. Directions for further research

Promising areas of further research include:

1. Development of new and improvement of the existing idealized model of the electrical network.
2. Study of fractal-cluster properties of real-life electrical networks. Determination of their characteristic indicators, such as fractal dimension, spatial scale, self-similarity properties, etc.
3. Determination of the influence of fractal-cluster properties of electrical networks on their technical and economic indicators
4. Establishing correlations between idealized models and real electric me-modes.
5. Development of algorithms for calculating the parameters of the modes of operation of the proposed model under real operating conditions.
6. Determination of technical and economic performance indicators of the proposed idealized network model under real operating conditions (determination of reliability, efficiency, safety, etc.)
7. Analysis and improvement of circuit solutions of network models and determination of their technical and economic indicators.

Conclusions

1. An idealized model of a branched distribution network is proposed, which is built on the basis of a fractal-cluster principle on the basis of a regular fractal with a basic elementary cluster in the form of a regular hexagon.
2. The algorithm for calculating the electric power of the base cluster of the proposed network model is determined.
3. Fractal properties and numerical indicators of the idealized model are determined.
4. The nomenclature of optimal voltages of electric network levels of the proposed idealized model is determined.
5. Calculations of these indicators were carried out.
6. Promising directions for further research are planned.

References

[1] Aldaikh, S. O., et al.: Study of starting modes of single-phase induction motors when changing the parameters of the stator windings, phase-shifting capacitor and supply voltage. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, 14(2), 2024, 34–41 [https://doi.org/10.35784/iapgos.5928].

[2] Alhamrouni I., et al.: A Comprehensive review on the role of artificial intelligence in power system stability, control, and protection: Insights and future directions. Applied Sciences 14(14), 2024, 6214. [https://doi.org/10.3390/app14146214].

[3] Amrane A. A., Retiere N., Riu D. M.: New modeling of electrical power networks using fractal geometry. 14th International Conference on Harmonics and Quality of Power – ICHQP 2010, Bergamo, Italy, 2010, 1–5 [https://doi.org/10.1109/ICHQP.2010.5625440].

[4] Babič M., et al.: A new method of quantifying the complexity of fractal networks. Fractal Fract. 6, 2022, 282 [https://doi.org/10.3390/fractalfract6060282].

[5] Budanov P. F., Brovko K. Yu.: Fractal-cluster analysis method for detecting disturbances in the operation of electric power equipment of power facilities. Visnic of the Kharkov National Technical University of Agriculture named after Peter Vasilenko. Technical sciences. Problems of energy security and energy saving in the agro-industrial complex of Ukraine 187, 2017, 92–94.

[6] Budanov P., et al.: Building a model of damage to the fractal structure of the shell of the fuel element of a nuclear reactor. Eastern-European Journal of Enterprise Technologies 4(8(118)), 2022, 60–70 [https://doi.org/10.15587/1729-4061.2022.263374].

[7] Castillo O., Melin P.: Hybrid intelligent systems for time series prediction using neural networks, fuzzy logic, and fractal theory. IEEE Transactions on Neural Networks 13(6), 2002, 1395–1408 [https://doi.org/10.1109/TNN.2002.804316].

[8] Florea G.: A Fractal Model for Power Smart Grids. 20th International Conference on Control Systems and Computer Science, Bucharest, Romania, 2015, 572–577 [https://doi.org/10.1109/CSCS.2015.104].

[9] Heshmatzadeh M., Lotfi-Neyestanak A. A., Noghanian S.: Improving Wireless Power Transfer Efficiency Using Fractal Metamaterial for Wearable Applications. IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI), Portland, OR, USA, 2023, 535–536 [https://doi.org/10.1109/USNC-URSI52151.2023.10237506].

[10] Hou H., et al.: Electric power network fractal and its relationship with power system fault. Zhaoyang Tehnički vjesnik 22(3), 2015, 623–628 [https://doi.org/10.17559/TV-20150427180553].

[11] Huang S.-J., Lin J.-M.: Application of box counting method-based fractal geometry technique for disturbance detection in power systems. IEEE Power Engineering Society General Meeting (IEEE Cat. No.03CH37491), Toronto, ON, Canada 3, 2003, 1604–1608 [https://doi.org/10.1109/PES.2003.1267395].

[12] Khasawneh A., et al.: Optimal Determination Method of the Transposition Steps of An Extra-High Voltage Power Transmission Line. Energies 14, 2021, 6791 [https://doi.org/10.3390/en14206791].

[13] Khomenko I. V. et al.: Electricity of Ukraine. Structure, management, innovation. NTU KhPI, LLC Planet-Print, Kharkiv 2020.

[14] Sang-Hoon Kim. Fractal structure of a white cauliflower. Journal of the Korean Physical Society 46(2), 2005, 474–477.

[15] Lezhnyuk P. D., Komar V. A., Sikorskaya O. V.: Distributed generation in the tasks of improving the energy efficiency of distribution electrical networks. VNTU, Vinnitsa 2023.

[16] Li B.-G., Yu Z.-G., Zhou Y.: Fractal and multifractal properties of a family of fractal networks. J. Stat. Mech. Theory Exp. 2, 2014, P02020 [https://doi.org/10.1088/1742-5468/2014/02/P02020].

[17] Liu C., Li D.: The Chaos and Fractal Characteristics and Predication of Shearer Load Power. International Conference on Electrical and Control Engineering, Wuhan, China, 2010, 5696–5699 [https://doi.org/10.1109/iCECE.2010.1384].

[18] Ma J., Wang Z.: Application of Grille Fractal in Identification of Current Transformer Saturation. Power System Technology 31(14), 2007, 84–88.

[19] Mamishev A., Russell Carl D., Benner L.: Analysis of High Impedance Faults Using Fractal Techniques. IEEE Transactions on Power Systems 11(1), 1996, 435–440 [https://doi.org/10.1109/59.486130].

[20] Markowska K., et al.: Analysis and improvement of power quality in the onboard electrical power systems within a self-propelled floating crane. International Journal of Electrical Power & Energy Systems, 161, 2024, 110179 [https://doi.org/10.1016/j.ijepes.2024.110179].

[21] Miroshnyk O., et al.: Investigation of Smart Grid Operation Modes with Electrical Energy Storage System. Energies 16, 2023, 2638. [https://doi.org/10.3390/en16062638].

[22] Nurujjaman A. H., Payer A.: A Review of Fractals Properties: Mathematical Approach. Science Journal of Applied Mathematics and Statistics 5(3), 2017, 98–105 [https://doi.org/10.11648/j.sjams.20170503.11].

[23] Ortjohann E., et al.: Cluster fractal model - A flexible network model for future power systems. International Conference on Clean Electrical Power (ICCEP), June 2013, 293–297 [https://doi.org/10.1109/ICCEP.2013.6587004].

[24] Sidqi Y., et al.: Comparing fractal indices of electric networks to roads and buildings: The case of Grenoble (France). Physica A: Statistical Mechanics and its Applications 531, 2019, 121774 [https://doi.org/10.1016/j.physa.2019.121774].

[25] Song C., Havlin S., Makse H. A.: Origins of Fractality in the Growth of Complex Networks. Nat. Phys. 2 2006, 275–281 [https://doi.org/10.1038/nphys266].

[26] Wang F., et al.: Fractal Characteristics Analysis of Blackouts in Interconnected Power Grid. IEEE Transactions on Power Systems 33(1), 1085–1086 [https://doi.org/10.1109/TPWRS.2017.2704901].

[27] Wang Z., Ma J.: A Novel Method to Identify Inrush Current Based on Grille Fractal. Power System Technology 31(11), 2007, 63–68.

[28] Wu Z., et al.: Patrol robot path planning in nuclear power plant using an interval multi-objective particle swarm optimization algorithm. Applied Soft Computing 116, 2022, 108192 [https://doi.org/10.1016/j.asoc.2021.108192].

[29] Yang G., et al: Typical Power Quality Disturbance Identification Based on Fractal Box Dimension. International Workshop on Chaos-Fractals Theories and Applications, Shenyang, China, 2009, 412–416 [https://doi.org/10.1109/IWCFTA.2009.93].

[30] Zengping W., Jing M.: A New Adaptive Method to Identify Inrush Using Grille Fractal. IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 2007, 1–5 [https://doi.org/10.1109/PES.2007.386041].

[31] Zhu H., Ji C.: Fractal theory and its applications. Science Press, Beijing 2011.

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