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Algorithms for building distribution networks of electricity supply, reducing losses of electricity

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Abstract

The basis for achieving high quality of electricity are three components: high-quality power generation, uninterrupted transmission and distribution over reliable networks. In conditions of commensurability of the power of electric motors with the power supply and with a considerable extension of the cable network, algorithms for automated design of the power supply system are needed. This article describes an approach based on the application of the Dijkstra algorithm, which allows to reduce costs in the construction of the distribution network and provide the necessary voltage level at the motor terminals or minimum energy losses in the cable network. The main and arbitrary structure of a power supply network with an electric load in terms of the theory of the genetic algorithm is described, on the basis of which it is possible to create an effective means of determining rational configurations of a power supply network with an electric load

Keywords: arbitrary structure, genetic algorithm, electric load, electric power distribution, electric power supply network, main structure, model, optimization, smart grid

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1. Introduction

Recently, a direction has been developing, related to the transformation of electricity based on a new concept, called the Smart Grid. Smart Grid should provide the required quality of electricity and increase the efficiency of the energy system as a whole, should be flexible, economical and have active elements that allow changing the topological parameters of the network.

The development of industrial enterprises is associated with the modernization of technological equipment. In these conditions, measures are needed to improve the rationalization of power supply systems. In networks, which are loaded with electric motors, the duration of starting the electric motor depends not only on the mechanical characteristics of the electric motor and the load, but also on the parameters of the elements of the network, and on its configuration. With one configuration of the network, a situation may arise where a decrease in the voltage at the motor terminals leads to a significant reduction in the starting torque. Starting the electric motor in such conditions becomes impossible. Reducing the voltage leads to an increase in the duration of starting the motor. Also, the electric power network configuration changes the power losses in the cables.

To date, the problem of electricity losses in distribution networks with electric load remains open, despite numerous studies in this area. A lot of methods, models and algorithms have been developed to improve the efficiency, reliability and safety of power distribution networks, and to optimize electricity losses for industrial enterprises. In [1-8], optimization of operating conditions of elements of power supply systems is described. This is achieved by integrating the parameters and characteristics of the power supply system, restructuring its structure, regulating voltage and reactive power. The issues of constructing active-adaptive networks and Smart Grid using neural networks and a genetic algorithm are given a large place in [9-12].

Until now, power supply systems with electric load are not sufficiently studied objects from the point of view of constructing rational configurations of the power supply network, taking into account the processes that arise when the limited power source and asynchronous motors work together in different operating modes. The reason for this situation is that the methods of calculating power supply systems were based on the average statistical values of the

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load without taking into account the instantaneous values of the coordinates of electric drives and the transformer because of insufficient perfection of computer facilities. This did not allow to synthesize rational configurations of the power supply network taking into account dynamic processes.

Enterprises receive losses from electricity losses in networks, without having the opportunity to assess their exact value due to errors associated with the calculations without taking into account the dynamic operating modes. Therefore, when changing the composition of equipment included in the work or when upgrading existing schemes, an effective calculation of losses is possible with more complete information on the parameters of the operating mode of electrical equipment, which can be obtained using a dynamic model of the power supply system.

By changing the connection points of flexible motor cables, it is possible to find the optimal configuration of the power supply network with a certain optimality criterion. The general formulation of the problem of optimizing the power supply network is to determine the coordinates of the connection of motor cables for given modes and parameters of asynchronous electric drives of industrial installations, the given coordinates of the location of the power source and electric motors, and also with the known layout of the electrical equipment. As an optimality criterion one can consider, for example, the criterion of minimum energy losses in the cable network or the criterion of minimum voltage losses in the cable network.

In addition, the division of the electric circuit modes into steady-state and transient processes is conditional. In the steady-state mode of a real system, its parameters are constantly changing, which is associated with changes in load and with the disconnection and connection of electric motors. Thus, in steady-state regimes in the system, small perturbations of the parameters of its regime are always possible, under which the system must remain stable. In normal modes with small perturbations, it is necessary to check the static stability of large groups of induction motors. Having the power commensurate with the power of the sources supplying them, these consumers may be unstable.

The conditions for the existence of a steady state are related to the power balance in the electrical system. The active and reactive power generated by the system's sources must be equal to the total power absorbed in the loads and dissipated in all elements of the system. The balance of active and reactive generation powers corresponding to the load capacities is violated in transient processes. In the power balance equation, two terms appear, reflecting free changes in electromagnetic energy in all elements of the system and changes in the mechanical energy stored in the rotating masses of the machines of the system.

In the steady state, the energy that enters the system from the outside is consumed in the load and goes to cover the losses. When there is any disturbance, manifested in the change in the parameter that determines the regime, this balance is violated. Steady will be those modes in which, when perturbed, factors that seek to break the mode change more slowly than the factors that counteract this violation. All this should be taken into account when designing or optimizing the existing power supply network.

After finding the optimal configuration using a dynamic model of a set of asynchronous motors, it is necessary to construct and investigate the dynamic characteristics of the transient processes of starting, braking, changing the load, and so on. On the basis of these characteristics, we can conclude that the system is static, by estimating the curves of the transient processes before and after optimization. Similarly, emergency modes can be simulated to test the dynamic stability of the system. In the program for finding the optimal network configuration, the boundary conditions must be introduced, for example, by the limit of the permissible voltage drop to ensure the stability of the operation of induction motors. In this case, if the optimal configuration of the power supply network proves to be unstable, the search process continues until another configuration, close to the optimal, is obtained, which will pass the stability test.

Calculation of the dynamic characteristics of induction motors of industrial enterprises for the analysis of the stability of power supply systems and the prediction of static and dynamic stability when changing the configuration of the network is given much attention in [13-15].

In connection with the above problems, algorithms for calculating the configuration of the power supply network are necessary, which allow you to take into account load characteristics in different operating modes.

2. Using the Dijkstra algorithm for building a distribution network

We will describe the approach based on the application of the Dijkstra algorithm, which allows to reduce the costs for the construction of the distribution network and provide the necessary level of voltage at the terminals of electric motors. Dijkstra's algorithm is an algorithm on the graphs invented by the Dutch scientist E. Dijkstra in 1959. He finds the shortest distance from one of the vertices of the graph to all the others.

This algorithm can be used at the stage of forming the initial configuration of the power supply network, which can later be optimized using the genetic algorithm described below.

The task of optimizing a network with an electric load is to select one of the whole set of network configurations, minimized in cost, that is, finding the minimum path weight from the root node (transformer) to each node of the distribution network (electric motor). The nodes of the distribution network correspond to the locations of the electric motors, and also are determined by the topology of the possible ways of routing the cables from the transformer to the electric motors (Figure 1).

The objective function in the Dijkstra algorithm is determined by the weight of each of the paths starting at the root node (transformer). The criterion of optimization is the minimum weight of the path from the root node to each node of the distribution network (electric motor).

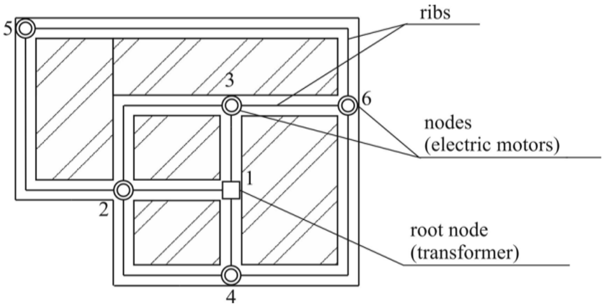

Figure 1. Nodes and edges of the electricity distribution network with electric load

The weight at the current step is selected based on the minimum weight of the path in the previous step or the sum of the weights of the path to the previous step and the next minimum edge.

Let us consider an example of finding the shortest paths from vertex 1 (transformer) for a graph in Figure 2, compiled from Figure 1.

At the first stage of the method implementation, a matrix of weights of edges (the lengths of the shortest arcs of the graph) of the initial network to be optimized is formed (Table 1). The starting point is the vertex 1, from which the tree of shortest paths is constructed. This operation is performed taking into account the topological features of the deployment area of the distribution network, and also taking into account the location of the motors.

At the second stage, the Dijkstra algorithm is executed. The optimization procedure is as follows. At each step, paths with a minimum weight from the root node to all other nodes of the network are defined.

We set the starting conditions: d(1) = 0, d(x) = ∞.

We include vertex 1 in the current tree, y = 1.

Find the nearest vertex to vertex 1, using the formula:

d(x) = min{d(x);d(y) + a(y,x)}.

d(2) = min{d(2);d(1) + a(1,2)} = min{∞;0 + 10} = 10;

d(3) = min{d(3);d(1) + a(1,3)} = min{∞;0 + 18} = 18;

d(4) = min{d(4);d(1) + a(1,4)} = min{∞;0 + 8} = 8;

d(5) = min{d(5);d(1) + a(1,5)} = min{∞;0 + ∞} = ∞;

d(6) = min{d(6);d(1) + a(1,6)} = min{∞;0 + ∞} = ∞.

The minimum length is the path from vertex 1 to vertex 4 d(4) = 8. Include vertex 4 in the current tree, and also the arc leading to this vertex. According to the calculations, this is an arc (1,4).

d(2) = min{d(2);d(4) + a(4,2)} = min{10;8 + 9} = 10;

d(3) = min{d(3);d(4) + a(4,3)} = min{18;8 + ∞} = 18;

d(5) = min{d(5);d(4) + a(4,5)} = min{∞;8 + ∞} = ∞;

d(6) = min{d(6);d(4) + a(4,6)} = min{∞;8 + 12} = 20.

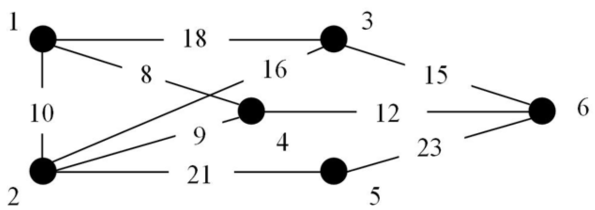

Figure 2. The graph corresponding to Figure 1

Table 1. The matrix of the weights of the edges

∞	10	18	8	∞	∞
10	∞	16	9	21	∞
18	16	∞	∞	∞	15
8	9	∞	∞	∞	12
∞	21	∞	∞	∞	23
∞	∞	15	12	23	∞

The minimum length is the path from vertex 1 to vertex 2 d(2) = 10. Include vertex 2 in the current tree, and also the arc leading to this vertex. According to the calculations, this is an arc (1,2).

d(3) = min{d(3);d(2) + a(2,3)} = min{18;10 + 16} = 18;

d(5) = min{d(5);d(2) + a(2,5)} = min{∞;10 + 21} = 31;

d(6) = min{d(6);d(2) + a(2,6)} = min{20;10 + ∞} = 20.

The minimum length is the path from vertex 1 to vertex 3 d(3) = 18. Include vertex 3 in the current tree, and also the arc leading to this vertex. According to the calculations, this is an arc (1,3).

d(5) = min{d(5);d(3) + a(3,5)} = min{31;18 + ∞} = 31;

d(6) = min{d(6);d(3) + a(3,6)} = min{20;18 + 15} = 20.

The minimum length is the path from vertex 1 to vertex 6 d(6) = 20. Include vertex 6 in the current tree, and also the arc leading to this vertex. According to calculations this arc (4,6).

d(5) = min{d(5);d(6) + a(6,5)} = min{31;20 + 23} = 31.

The minimum length is the path from vertex 1 to vertex 5 d(5) = 31. Include vertex 5 in the current tree, and also the arc leading to this vertex. According to the calculations, this is an arc (2,5).

We have obtained a tree of shortest paths starting at vertex 1 for the original graph.

d(1) = 1: path length L = 0;

d(2) = 1-2: path length L = 10;

d(3) = 1-3: path length L = 18;

d(4) = 1-4: path length L = 8;

d(5) = 1-2-5: path length L = 31;

d(6) = 1-4-6: path length L = 20.

A tree with a root in vertex 1 is shown in Figure 3.

As a result, the structure of the distribution network is obtained with a minimum weight of the path from the root node to each node of the distribution network. As a result of the algorithm, the minimum cost of construction of the distribution network is formed, taking into account the binding to the terrain.

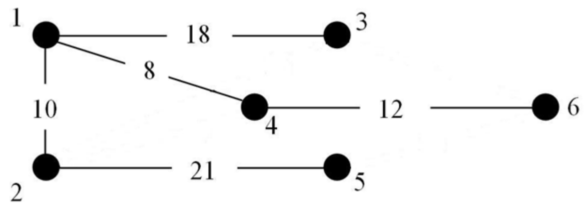

Figure 3. Tree with root in vertex 1

3. Description of the main structure of the power supply network in terms of the theory of the genetic algorithm

On the way to the implementation of the Smart Grid concept, the models of a power supply network for the main and arbitrary structures feeding asynchronous motors with a squirrel-cage rotor have been developed [13, 14].

We will describe the main structure of the electric power supply network with the electric load, the mathematical model of which is given in [13], in terms of the theory of the genetic algorithm.

The power supply network is characterized by external and internal parameters. In finding the specific values of the internal parameters (the coordinates of connecting the motor cables), the process of determining the rational configurations of the power supply network consists. The initial data for the work of the genetic algorithm are the topological scheme of the location of electrical equipment with the indication of possible trajectories of the engine cables, the parameters and operating modes of the electric drives, the parameters of the transformer.

To select from the search for the best feasible solutions, an optimality criterion is formulated. In the problem of determining the rational configurations of the power supply network, the solution is a set of numbers, each of which means the distance from the transformer to the place where the cable of a certain electric motor is connected to the trunk cable laid to the electric motor remote from the transformer.

The application of the genetic algorithm, involves the stage of creating the initial population (m initial solutions): $\{x_1^1, x_2^1, \ldots, x_n^1\}$, $\{x_1^2, x_2^2, \ldots, x_n^2\}$, $\{x_1^m, x_2^m, \ldots, x_n^m\}$, where n is the number of engines in the system. In the future, a transition is made from the vector of parameters $\{x_1^m, x_2^m, \ldots, x_n^m\}$ to a vector $\{s_1^m, s_2^m, \ldots, s_n^m\}$ with integer components. When moving from an integer vector $\{s_1^m, s_2^m, \ldots, s_n^m\}$ to a binary alphabet, the Gray code is used.

By concatenating the lines s_1, s_2, ..., s_n, where each value s_i $(i = \overline{1,n})$ is encoded by the Gray code, m chromosomes are formed in the population with the number of $l = n \times \theta$ genes in each chromosome, where θ is the length of the binary word encoding the integer s_i. Thus, the solution corresponds to a bit string – a chromosome, which is one of the possible configurations of the power supply network.

The genetic algorithm performs three basic operations: re-production, crossing and mutation. Reproduction is the process of selecting the rows $K \cdot m$ of the population $G(t)$, where K is the coefficient of nocturnality. The probability of choosing the row S_j^t is proportional to its value:

$$_{в}(S_j^t) = \frac{(S_j^t)}{\sum_{k=1}^{m} (S_k^t)}$$

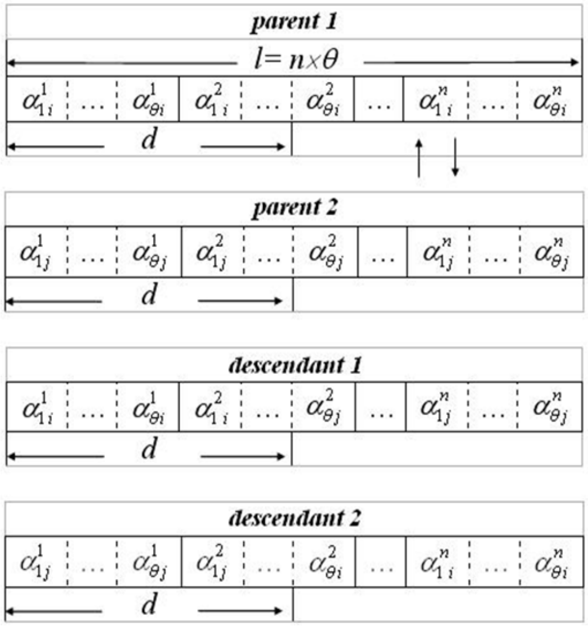

Figure 4. Crossing operation

The rows i and j $(i, j = \overline{1,m})$ selected at the stage of reproduction are randomly grouped into pairs (parents). Each pair with a given probability p_c is then crossed. When crossing, a random selection of the position of the separator d (d=1, 2, ..., l-1, where l is the length of the line) occurs.

Then the values of the first d elements of the first row are written to the corresponding elements of the second one, and the values of the first d elements of the second row are written into the corresponding elements of the first. The result is two new rows (descendants), shown in Figure 4.

A mutation is a process of randomly changing the values of the elements of a string. For this, the lines obtained at the crossing stage are viewed element by element, and each bit with a given probability of mutation p_m can mutate, that is, change its value to the opposite. The mutation process is shown in Figure 5.

As a result of the operations described above, $K \cdot m$ new rows are obtained, either completely forming a new population $G(t+1)$ (for K=1) or forming part of the population $G(t+1)$ (for K<1).

The new population is recorded over the old population. This cycle of one generation is completed. If the new generation contains a solution sufficiently close to the answer, then the problem is solved. Otherwise, it passes through the above process.

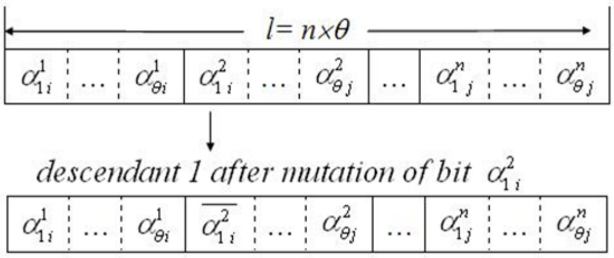

Figure 5. Operation of a mutation

This continues until the best solution remains unchanged for a given number of generations, or a different stop condition (for example, a certain number of generations) is satisfied. After that, the best solution is considered close to the optimal solution, that is, rational.

4. Description of an arbitrary structure of the power supply network in terms of the theory of the genetic algorithm

We will also describe an arbitrary structure of a power supply network with an electric load, the mathematical model of which is given in [17], in terms of the theory of the genetic algorithm.

The above Dijkstra algorithm determines the network structure, which remains unchanged with further optimization. Quantitative changes occur only with cable lengths in accordance with the genetic search algorithm.

On the basis of the foregoing, there is a need for the formation of an individual containing qualitative and quantitative parameters of a given structure of the power supply network.

Consider the mechanism of formation of the individual.

Any configuration of a network with N electric motors when powered by a single transformer can be represented in the form of the structure shown in Figure 6.

Figure 6 shows: N – the number of electric motors in the network; s is the number of levels in the network; j, k, l is the motor serial number, $\in [1; N]$, $k \in [1; N]$, $l \in [1; N]$. The numbering of the motors is from left to right and from top to bottom. Node – the place of connection of cable lengths. The cable segment is the cable section between the nodes. Up to the N-th electric motor from the transformer, the greatest number of cable lengths.

First, the given configuration of the power supply network must be presented in the form of the structure shown in Figure 6. For this purpose, it is necessary to select the electric motor to which the maximum number of cable segments is from the transformer as the last N-th electric motor. After that, the electric motors are assigned serial numbers. If there are no motors or cable lengths in the specified power supply network, represented in the form of the structure shown in Figure 6, the parameters of these motors and cable lengths are assigned zero values.

After drawing up the structure of the power supply network, the following parameters are determined: s – number of levels in the network; f_1 – number of cable segments of the first level, $f_1=s$; c – number of points of connection of cables of electric motors of the second level to the cable of the first level, $c=f_1-1$; N is the number of electric motors in this network structure, $N=2^c$.

If the motor is at the first level, then it is connected to the transformer. If the motor is at the second level, then it is connected to the first level cable. The number of points of connection of cables of electric motors of the third level to any second-level cable does not exceed f_1-2. The number of points for connecting cables of i-level motors to the i-1-level cable does not exceed f_1-i.

Gene – a section of cable between the two nearest nodes. The value of the gene corresponds to the length of this segment. The original lengths of the segments, i.e. the original values of the genes, are set at the stage of the power supply network representation in the form of the structure depicted in Figure 6. The cable segment connected to the transformer is considered a genome, and cable lengths connected to electric motors are not considered genes. When the genetic algorithm works, the gene value varies from zero to the original value of the gene. The number of genes in the network is one less than the number of electric motors ($N-1$).

The chromosome is a collection of genes of one level lying on the path from the transformer to the electric motor. In this case, the length (number of genes in the chromosome) of a single chromosome of the first level is c. The length of any chromosome of the second level does not exceed c-1. The maximum length of the i-th chromosome is c-i+1. The number of chromosomes in the network is half the number of electric motors ($N/2$).

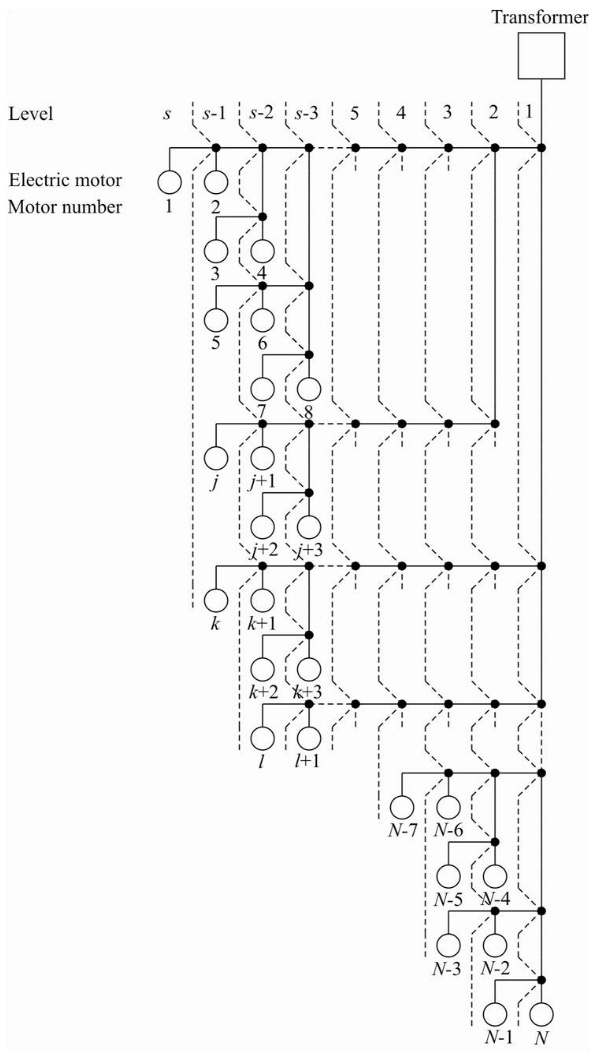

Figure 6. Electric power supply network of an arbitrary structure with an electric load

Table 2. Formation of an individual

level	1				2										…
chromosome number at the level	1				1				2				…	$\sum_{i_1=c-1}^{1} 1$	…
chromosome number in the individual	1				2				3				…	$1+\sum_{i_1=c-1}^{1} 1$	…
gene number in chromosome	1	2	…	c	1	2	…	c-1	1	2	…	c-2	…	1	…
gene number at the level	1	2	…	c	1	2	…	c-1	c	c+1	…	2c-3	…	$\sum_{i_1=c-1}^{1} i_1$	…
gene number in the individual	1	2	…	c	c+1	c+2	…	2c-1	2c	2c+1	…	3c-3	…	$c+\sum_{i_1=c-1}^{1} i_1$	…

Table 3. Formation of an individual (table 2 continuation)

…	c
…	1
…	$1+\sum_{i_1=c-1}^{1} 1+\sum_{i_1=c-2}^{1}\sum_{i_2=i_1}^{1} 1+\sum_{i_1=c-3}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1} 1+\cdots+\sum_{i_1=c-n}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1}\dots\sum_{i_n=i_{n-1}}^{1} 1+\cdots+\sum_{i_1=2}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1}\dots\sum_{i_{c-2}=i_{c-3}}^{1} 1$ or 2^{c-1}
…	1
…	1
…	$c+\sum_{i_1=c-1}^{1} i_1+\sum_{i_1=c-2}^{1}\sum_{i_2=i_1}^{1} i_2+\sum_{i_1=c-3}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1} i_3+\cdots+\sum_{i_1=c-n}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1}\dots\sum_{i_n=i_{n-1}}^{1} i_n+\cdots+\sum_{i_1=2}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1}\dots\sum_{i_{c-2}=i_{c-3}}^{1} i_{c-2}$ or 2^c-1

The individual is the aggregate of all chromosomes. The individual fully describes the electricity supply network and is the only one.

The number of genes in an individual is determined by the formula:

$$G=c+\sum_{i_1=c-1}^{1} i_1+\sum_{i_1=c-2}^{1}\sum_{i_2=i_1}^{1} i_2+\sum_{i_1=c-3}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1} i_3+\cdots+\sum_{i_1=c-n}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1}\dots\sum_{i_n=i_{n-1}}^{1} i_n+\cdots+\sum_{i_1=2}^{1}\sum_{i_2=i_1}^{1}\sum_{i_3=i_2}^{1}\dots\sum_{i_{c-2}=i_{c-3}}^{1} i_{c-2}.$$

Each term in this expression determines the number of genes at the appropriate level: the first term – the number of genes at the first level, the second – at the second level and so on.

If we write the sums in the above formula, then in the resultant expression each term will determine the number of genes in the corresponding chromosome: the first term is the number of genes in a single chromosome of the first level, the second is the number of genes in the first chromosome on the top of the second level, the third in the second from the top chromosome of the second level and so on.

If we write out the corresponding term from the above expression, then the sum of the terms in the resulting expression will determine the number of chromosomes at the corresponding level.

The formation of an individual is shown in the tables 2 and 3. The last line from the table is an individual.

5. Conclusions

1. The presented Dijkstra algorithm can be used in the construction of power supply networks with electric load as a method of optimizing distribution networks.

2. Dijkstra's algorithm should be applied at the stage of forming the initial configuration of the power supply network, which can later be optimized using a genetic algorithm.

3. It is advisable to use the genetic algorithm when searching for the quantitative parameters of a given structure of the power supply network.

4. The above expressions form a description of the power supply network in terms of the theory of the genetic algorithm, on the basis of which it is possible to create an effective means for determining rational configurations of a power supply network with an electric load.

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