

Methods for the Formation of Calculation Models of Electric Power Systems in the Adequacy Assessment Problem

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Abstract. The article deals with the problem of generating calculation models (CM) of electric power systems (EPS) into reliability zones, designed to perform calculations of adequacy assessment indicators. The substantiation of the depth of detail of the CM is based on taking into account two properties of the EPS: reliability, namely, on the basis of calculated estimates of the limits of applicability of deterministic and probabilistic reliability and efficiency criteria, namely, on the basis of a comparison of cost estimates of measures to ensure reliability. To solve this problem, it is proposed to use a number of so-called engineering algorithms, which take into account the reliability and efficiency of the EPS. The experimental part presents the results of applying the proposed algorithms for the formation of the CM analyzed by the EPS.

1 Introduction

The formation of calculation models (CM), in the general case, is justified by the large dimension of the task of assessing and synthesizing adequacy and by the maximum reduction of the network component, which has little effect on the adequacy indicators. The formation of CM should be based on the structure of the electric power system (EPS), technical and reliability characteristics of the elements, regime and economic features of the operation of the EPS. CM are presented in the form of multi-zone models, including reliability zones (RZ) and inter-zone communications (ZC). RZ includes a part of the EPS, within which restrictions are unlikely in the transmission of active power in all possible modes for the period of the assessment of the adequacy. RZ contains a certain number of power stations and a certain load of consumers. ZC is a set of power transmission lines (TL) between RZ. Units at power plants, the load of consumers in the RZ and power lines in interzone connections when assessing the adequacy, are characterized by a certain set of reliability and technical parameters taken into account when assessing the adequacy.

In fact, the procedure for determining the CM into reliability zones and the formation of the CM is one of the stages in the adequacy assessment, since the correctness of the determination of the CM directly affects the indicators of adequacy and further problem solving based on the obtained adequacy indicators (AI), for example, justifying the redundancy level of generating capacity. The methodology for adequacy assessment, taking into account the stage of determining the CM based on the Monte Carlo method,

in general, will represent the following sequence of computational steps:

1. Formation of CM (per-node) EPS into reliability zones.
2. Formation of a set of random states of the EPS for the period of adequacy assessment.
3. Minimization of the power deficit of the calculated states of the EPS.
4. Calculation of AI.

As a rule, the adequacy assessment is carried out for an annual period, taking into account many parameters that affect the reliability of the EPS, including the hourly power consumption change schedule, which for different RZs can have significant changes during the year. A change in the parameters taken into account during the analyzed period can have a significant impact on the AI values and, accordingly, form the requirements for the multiple formation of CM in the adequacy assessment cycle.

As already noted, the task of forming the CM is one of the keys in the entire process of adequacy assessment. The correctness of the obtained AI and the validity of subsequent actions depend on the correctness of its solution. Let us dwell on some aspects of the Russian practice of forming the CM. Initially, the adequacy assessment was carried out by representing the analyzed EPS of one RZ. In this case, the reliability of only generating sources and the probabilistic characteristics of the load of consumers were taken into account [1,2]. The representation of CM in this form is explained by the lack of methodological developments for the analysis of multizone models and the insufficient computing base for solving more complex problems. Most of the existing approaches to the formation of CM are of an expert nature and are based on the organizational

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principles of EPS management. For example, one of the approaches to the formation of the CM of the Unified Energy System (UES) of Russia is its division into 7 reliability zones, where each zone corresponds to one of the unified energy systems (IPS) included in the UES of Russia. The connections between them consist of intersystem transmission lines. With the introduction of market relations in the domestic electric power industry, attempts were made to form a CM for adequacy assessment in accordance with the free flow zones, but the division of the UES in this way, despite the deeper detail, does not have a rigorous justification for the purposes of adequacy assessment. From the standpoint of the information content of the CM, it is preferable to form the CM in such a way that each RZ represents the power system of a subject of the Russian Federation [3]. In all the above methods of forming the CM of the UES of Russia, a number of questions remain open, including the determination of the bandwidth of the ZC.

It is worth noting the foreign practice of forming the CM. For example, in the United States, the assessment of adequacy is carried out for a twenty-zone calculation model [4, 5]. The formation of reliability zones was carried out expertly using a representative sample of retrospective information about the functioning and reliability of the US energy system. The European Association for the Cooperation of Operators of Transmission Systems for Electricity (ENTSO-E) generates reports on medium-term forecasts of the adequacy of the European energy system [6]. The scope of analysis includes ENTSO-E member countries (42 transmission system operators). The calculation scheme for the analysis of the adequacy is formed according to the borders of the energy systems of the states, i.e. in practice, the energy system of each state represents the RZ. For a more detailed analysis of the situation in the field of adequacy of energy systems within states, an additional division of energy systems into reliability zones is carried out, usually based on an expert approach.

The purpose of this article is to present and analyze a number of engineering algorithms for the formation of CM.

2 The Criterion for the Formation of the CM of the Electric Power System Into Reliability Zones

Substantially, the task of determining the CM is formulated as follows: for the known structure of the EPS, the characteristics of generating capacities and power consumption schedules, the limitations of the capacity of power transmission lines and sections of the electric network, the organizational and economic conditions for the functioning of the EPS, it is necessary to determine the boundaries of the RZ for the formation of the CM and further adequacy assessment.

Mathematically, the problem of determining the CM on the RZ can be formulated as follows: given $X = \{x_1, x_2, \dots, x_N\}$ – the set of nodes of the EPS

design scheme, specified in the k – dimensional space of features:

$$x^k = \{x_1^k, x_2^k, \dots, x_N^k\}, k = 1, \dots, K. \quad (1)$$

There is a distance function (metric) $\rho(x)$ between the nodes of the EPS design scheme. It should be understood that the distance functions are not a direct distance between the nodes of the calculation scheme. The distance function is formed from a set of operating characteristics of the power system, taken into account when determining the CM.

It is required to split the finite sample of nodes of the calculation scheme X into Z non-intersecting subsets:

$$S_z, z = 1, \dots, Z; X = \bigcup_{z=1}^Z S_z, \quad (2)$$

which form the RZ Z , in such a way that each RZ includes nodes whose metric ρ is less than the threshold value; otherwise, the nodes are sorted into different RZs.

In this case, each node $x_i \in X$ is assigned the number of the reliability zone $z_j \in Z$.

For the problem being solved, the most appropriate strategy would be the "divide and conquer" strategy, which consists in dividing the considered set into groups of similar objects. In the case under consideration, the number of reliability zones will tend to a minimum, i.e.:

$$Z \rightarrow \min. \quad (3)$$

When solving real practical problems, one must understand that the division of the system into reliability zones is conditional and depends on the criteria used that form the metric ρ .

3 Formation of CM Based on Controlled Sections

When managing a power system, there is a set of controlled sections (a set of parallel connected network elements), the loading of which during operation is controlled by the system operator for not exceeding the maximum allowable flow, determined by the criteria for the allowable current load of the elements, static and dynamic stability in normal and post-emergency modes [7]. Based on taking into account the controlled sections, the algorithm for dividing the EPS into RZs can be presented in the following form:

1. Formation of the composition of the electrical network elements included in the specified controlled sections.

2. Identification of the EPS reliability zones based on the composition of the EPS elements specified in clause 1. If an object or a set of EPS objects (stations, substations) is separated by a controlled section or a set of EPS objects (stations, substations) or a set of controlled sections from the rest of the EPS, then the object or a set of objects form a reliability zone.

3. Bandwidths of interzone connections are determined in accordance with the maximum allowable active power flows over controlled sections. The generating capacity and load of the reliability zone is formed from generating units and consumers included in the reliability zone.

This method of determining the CM is acceptable for the EPS development planning horizon up to 6 years, during which the EPS structure will change insignificantly and these changes are unambiguously determined by the development scheme and program [8]. The undoubted positive side when using this approach is the certainty with the bandwidth of the ZC, which are formed on the basis of the values of the maximum allowable active power flows.

4 Formation of CM Based on Express Analysis of Adequacy

The most common in the practice of designing and operating EPS are deterministic reliability criteria of the type "N-k" [9]. It is obvious that for modern EPS with a large number of elements, the use of deterministic criteria for the analysis of adequacy is unacceptable, since the modes corresponding to the criteria "N-1" and "N-2" cover only a small fraction of the possible states of such EPS. Nevertheless, these criteria are quite correct to apply for express adequacy assessment. In this case, the adequacy assessment using deterministic criteria can lead to an acceptable result.

Let us estimate the boundaries of the possible application of the "N-1" criterion for an energy district, the power supply of which is carried out from N elements of the EPS. When the criterion "N-1" is met, the design states of the system under consideration are all states with a failure of no more than one element out of N. The probability of deficit-free operation P in the case under consideration can be calculated by the formula:

$$P = \prod_i(1 - q_i) + \sum_i(q_i \cdot \prod_{j \neq i}(1 - q_j)), i = 1, \dots, I, \quad (4)$$

where q_i is the probability of an emergency state of the i -th element. The results of calculating P depending on N at $q_i = 0.02$ are shown in Table 1.

Table 1. Probability of calculated states according to the criterion "N-1"

N	P	N	P
2	0,9996	7	0,9921
3	0,9988	8	0,9897
4	0,9977	9	0,9869
5	0,9962	10	0,9838
6	0,9943		

According to Table 1, it can be noted that with the normative level of adequacy (the probability of deficit-free work (DFP) equal to 0.996 [10]), the analysis of adequacy using the criterion "N-1" is possible at $N \leq 5$. In this case, the total probability of all calculated states above 0.996, and if the "N-1" criterion is met, that is, if

there is no power shortage in case of failure of any one element, the specified standard level will be certainly provided. Accordingly, the allocation of energy districts, the power supply of which depends on 5 or less EPS elements, into separate RZs is not advisable. Deterministic criteria "N-k" can be correctly applied to the analysis of adequacy in relation to such energy regions.

The method based on the Monte Carlo method, but with a reduction in the number of analyzed conditions, can also serve as an express method for adequacy assessment. One of the main computational problems in applying the method for adequacy assessment based on the Monte Carlo method is the large dimension of the problem being solved, which leads to unreasonably high time costs. It should be noted that it is precisely because of the decrease in the dimension of the problem that the formation of the CM is required. When assessing adequacy based on the Monte Carlo method, they try to achieve a given accuracy criterion for each hour of the analyzed period [11,12]. For the EPS scheme, taking into account all nodes and transmission lines, for which the formation of the CM is carried out, this is an extremely time-consuming procedure, and in some cases simply impossible. In this case, one of the solution methods may be to simplify the problem, for example, to evaluate only for the hour of the maximum load of the EPS or for the monthly peaks of the load of the EPS and use the obtained indicators in determining the CM.

By definition, restrictions on power flows in the RZ are unlikely in all probable modes of operation of the EPS. From this it follows that if the DFP in adjacent nodes of the system take relatively close values, then such nodes can be combined into a reliability zone. The criterion in this case will be the value of the difference between the DFP in adjacent reliability zones:

$$\Delta = |P_i - P_j|, i = 1, \dots, n, j = 1, \dots, n, i \neq j, \quad (5)$$

where: n is the number of EPS nodes.

The algorithm for determining CM based on the proposed criterion will be as follows:

1. Adequacy assessment of the complete EPS scheme (a scheme with all nodes and power lines) using an express method.
2. Determination of the difference in the DFP between adjacent nodes of the EPS.
3. If the difference is greater than the specified criterion Δ , then such nodes are distributed over different reliability zones.
4. If the difference is less than the given criterion Δ , then such nodes are defined in one reliability zone.
5. If in ring connections the difference between adjacent nodes is inconsistent (i.e. between different nodes Δ takes values greater than or less than a given criterion), then such nodes are combined into one reliability zone.

One of the main tasks in the formation of CM is the determination of the bandwidth of the ZC. In the case of determining the CM on the basis of the controlled sections, discussed above, this problem is solved. In other approaches, this problem needs to be solved. In

the general case, the throughput of the ZC is determined in accordance with [7], in the absence of the necessary information for this, based on reference data [13] in accordance with the expression:

$$P_{max} = \min(P_{perm}; 0,8 \frac{U_r^2}{x_0 l}), \quad (6)$$

where P_{perm} is the maximum transmitted power under the conditions of a long-term permissible current load, adopted according to [13] (for a 500 kV transmission line - 1700 MW, for a 220 kV transmission line - 300 MW); U_r is rated voltage of power transmission lines, kV; x_0 – linear inductive resistance of power transmission lines (Ohm/km); l is the length of the power transmission line (km).

5 Formation of CM in Accordance with the Economic Criterion

As already noted, one of the main objectives of the adequacy assessment is to substantiate the need for EPS in generating capacities and their distribution over the RZ in accordance with the restrictions on power transmission over the ZC. If an insufficient level of adequacy is identified, investment decisions are made on the construction of new generating capacities, while their volume and location are determined, among other things, by the specified network restrictions. An alternative to the construction of new generating capacities in a specific reliability zone may be to strengthen the electrical connections incident to it, provided that there is a sufficient power reserve in adjacent zones.

From this we can conclude that when forming the CM, it is sufficient to take into account the restrictions on power transmission only for those sections of the electric network, the cost of strengthening which is comparable to the cost of building new generating capacities. Taking into account other network restrictions, the elimination of which is obviously characterized by less capital intensity, will not only lead to excessive detailing of the CM and complicate the procedures for assessing and analyzing adequacy, but can also potentially lead to inefficient investment decisions for the development of generating capacities. For example, if such decisions are due to local restrictions in the distribution network, taken into account in the CM, in the presence of excess power in the EPS as a whole.

In accordance with the above, we will perform an assessment of network restrictions, the consideration of which is economically feasible when justifying the boundaries of reliability zones in CM. As initial data for such an assessment, we use aggregated price standards for standard technological solutions for the capital construction of electric power facilities in terms of electric grid facilities [14] and indexed indicators of specific capital investments in gas generation generating facilities, which, as a rule, closes the power balance, according to [15].

For Russian conditions, according to [14], specific capital investments (SCI) in an overhead TL of a voltage class of 500 kV in a typical layout, taking into account the substation part, are estimated at 59 million rubles per 1 km of length, into a single-circuit power transmission line of a voltage class of 220 kV - 28 million rubles per 1 km of length in 2021 prices. SCI in generation according to [15], taking into account indexation for 2021 and verification for specific projects, is estimated at an average of 50 million rubles per 1 MW of installed capacity. The specified SCI values are given without taking into account the cost of land acquisition.

To calculate SCI per unit of throughput of power lines, it is required to set their throughput, which can be determined by (6). SCI per unit of transmission capacity of a transmission line depends on its length and is defined as the ratio of the cost of a transmission line, determined on the basis of SCI according to the data of [14], to the transmission capacity determined by formula (6).

The results of the performed calculations are shown in Figs. 1. On the presented graph, along the abscissa axis, the length of the transmission line is plotted, along the ordinate axis - SCI per unit of transmission capacity of the transmission line. The red and blue markers show the dependencies for the 500 kV transmission line and the 220 kV transmission line, respectively. The black dotted line indicates the SCI level in the generation.

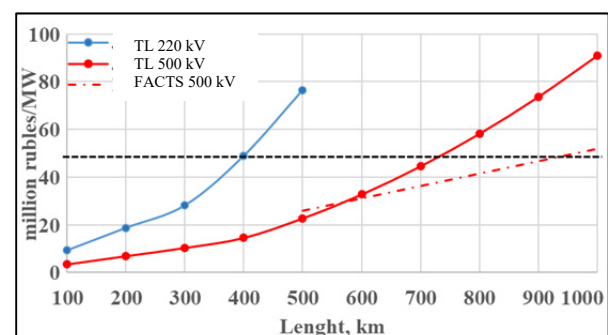


Fig. 1. Dependences of SCI per unit of transmission capacity of a transmission line on its length.

Considering the obtained dependencies, we can note the following. Dependences of SCI per unit of throughput for short transmission lines (up to 400 km for 500 kV transmission lines and up to 300 km for 220 kV transmission lines) are linear; This is due to the fact that for short transmission lines, the throughput is determined by the conditions of the permissible current load and does not depend on the length, and for long power lines, the throughput is determined by the stability conditions and decreases with increasing length, which leads to a quadratic increase in SCI. The SCI level in generation for a 500 kV transmission line is achieved with a length of about 750 km, for a 220 kV transmission line - with a length of 400 km.

Based on these results, an unambiguous conclusion can be made about the expediency of separating nodes located at a distance of more than 750 km into separate

RZ CM. In this case, if it is necessary to increase the AI, solutions for the construction of new generating capacities will definitely be more economical. The construction of a new transmission line of equivalent transmission capacity will require more costs and can only be justified taking into account additional effects, for example, optimizing the balance of electrical energy.

On the contrary, based on the proposed approach, it is advisable not to take into account the restrictions on power transmission through power lines up to 400 km long during the formation of CM, since the cost of strengthening such sections of the network is lower than the construction of new generating capacities in the corresponding volume.

It is necessary to consider in more detail the case in which the distance between the nodes is from 400 to 750 km. In this case, SCI for 500 kV transmission lines, as seen in Fig. 1, below SCI into generation. However, it should be taken into account that the cost of a 500 kV power transmission line of this length is 23.5 - 41 billion rubles, which corresponds to the cost of building a new generating facility with an installed capacity of 500 - 800 MW. Therefore, if the demand for power is below the specified range, then the construction of a new generation is more economical than a new transmission line.

Thus, based on the economic principle of detailing the CM, we can make the following recommendations for their formation:

1. EPS nodes located at a distance of up to 400 km should be combined into one RZ;
2. EPS nodes located at a distance of more than 750 km should be attributed to different RZs, restrictions on power transmission via power lines between them should be taken into account when determining the throughput of the corresponding ZC;
3. EPS nodes located at a distance of 400 to 750 km should be combined into one RZ if the potential need for the power of these nodes is more than 500 - 800 MW.

These recommendations can be adjusted taking into account the use of non-capital-intensive means of increasing the capacity of transmission lines. It is known that modern means of power flow control (phase-shifting devices, controlled reactive power compensation, etc.), collectively referred to in the literature as flexible alternating current transmission systems (FACTS), can significantly increase the capacity of long-distance transmission lines up to the permissible current load. At the same time, the coefficient of appreciation of such transmission lines due to the installation of appropriate devices, the construction of intermediate substations and switching points for them, based on the data of [12], can be estimated at 1.5. Then the dependence of SCI per unit capacity of long-range 500 kV transmission lines with FACTS will have the form indicated in Fig. 1 with a red dotted line.

Based on these results, when applying FACTS, the distance limit given in paragraph 1 can be increased to 1000 km. However, taking into account point 3 and the cost of such power transmission, it is advisable to

combine nodes located at a distance of 500 - 1000 km into one reliability zone only if the potential need for the power of these nodes is more than 1000 - 1500 MW.

6 Experimental Studies

We will show the operation of each of the proposed CM generation algorithms based on the application of the IEEE RTS-96 test circuit [16].

First, we will demonstrate the division of the EPS into reliability zones in accordance with the designation of controlled sections. Since the controlled sections are not defined for the scheme under consideration, they were determined by experts. The following shows the identification of reliability zones for a part of the scheme under consideration according to the algorithm presented in the article (Fig. 2).

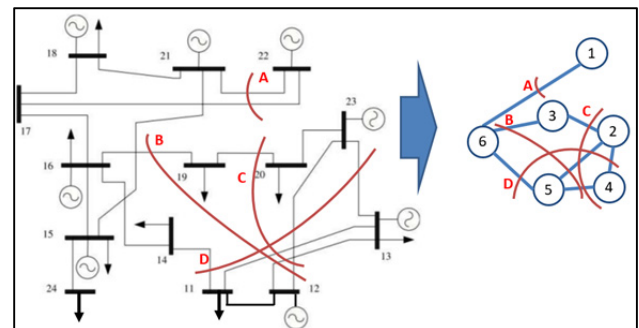


Fig. 2. Formation of CM into reliability zones along controlled sections.

Next, the formation of CM was carried out on the basis of the analysis of AI obtained by the express assessment method. In table 2 presents the probability values of a deficit-free operation of the nodes of the analyzed system.

Table 2. DFP of the considered EPS.

Node number	The probability of a deficit-free work	Node number	The probability of a deficit-free work
1	0,9661	13	0,9886
2	0,9676	14	0,9791
3	0,9656	15	0,9843
4	0,9696	16	0,9881
5	0,9674	17	0,9999
6	0,9681	18	0,9916
7	0,9917	19	0,9899
8	0,9688	20	0,9909
9	0,9729	21	0,9916
10	0,9717	22	0,9937
11	0,9999	23	0,9930
12	0,9999	24	0,9999

The value $\Delta=0.004$ was chosen as a criterion for the formation of CM. As a result, 12 reliability zones were obtained. Table 3 shows the attribution of nodes to the RZ, and in fig. 3 shows the formed RZs in the EPS scheme.

Table 3. Assignment of nodes to reliability zones.

RZ number	Node number	RZ number	Node number
1	1,2,3,4,5,6,8,9,10	7	15,16
2	7	8	17
3	11	9	19,20,23
4	12	10	18,21
5	13	11	22
6	14	12	24

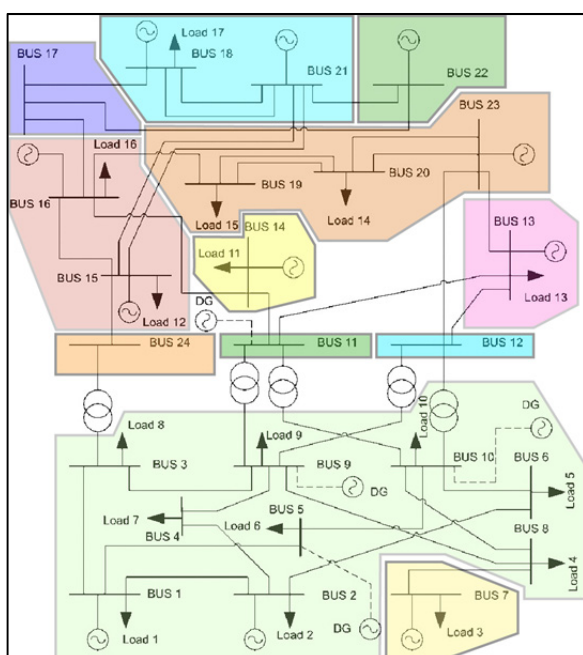


Fig. 3. The result of the formation of CM based on the express analysis of adequacy.

The next stage of experimental research is the formation of CM in accordance with the economic criterion. As a result, it turned out that the formation of CM according to this criterion for the considered EPS is impossible, since the distances between the nodes are less than 400 km, therefore, in the case of determining the optimal level of redundancy of the generating capacity, the system can be represented by one RZ.

7 Conclusion

In the present study, the problem of generating energy calculation models that are used in adequacy assessment of electric power systems is considered. The existing domestic and foreign practice of generating energy calculation models was analyzed and engineering methods for solving the problem under consideration were proposed.

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