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Electric Grids Technical Evaluation Method based on their Failure Probability

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Abstract. The article provides the substantiation of the necessity to develop a mechanism for determining the electric grid element with the lowest reliability taking into account the equipment operation peculiarities in the Russian Federation. Critical analysis of existing approaches to identifying dilapidated electrical equipment, as well as recommendations of the Ministry of Energy of the Russian Federation on assessing technical condition of electric networks has been carried out. It is proposed to determine the technical condition of electric grids by the value of their failure probability. Failure probabilities mathematical models for large groups of emergency modes are given: insulation failure, failure of current-carrying elements and failure due to mechanical damage, as well as for all electrical equipment on the whole. Criteria and an algorithm for mechanical defects of electric grids elements expert evaluation are presented. The calculation of the failure probabilities for two elements of real electric grid is made. The conclusions is made on the feasibility of replacing one of the considered elements.

1. Introduction

Today the situation in the Russian electric power industry is that a large part of the electric grid infrastructure is very outdated. Moreover, more than 70% of power lines and transmission substations have worked out their physical and moral resources to the utmost. Such electrical grids are characterized by frequent breakdowns resulting in an interruption in power supply which leads to huge material losses, both for electricity consumers and electric grid companies.

In order to reduce dangerous situations occurrence the electricity companies should timely repair electrical equipment. However it is impossible to timely repair all the equipment because of the limited financial resources coming from the electricity tariff [1-2]. Thus, in order to reduce the occurrence of emergency conditions and to minimize their consequences the grid companies must clearly identify the most unsatisfactory technical condition of the equipment [3-8].

At present in Russia the most common method of identifying unreliable electric grids equipment involves carrying out electrical parameters control measurements and their subsequent comparison with threshold regulatory values given in specialized scientific and technical documentation. However this approach to evaluating technical condition of electric grids is difficult to consider completely correct. For example, according to the rules of electrical installations the insulation resistance of cables with voltage up to 1 kV during control measurements should not be less than 0.5 MΩ, otherwise its further use is prohibited. But the existing experience in operating cable lines shows that the cable does not fail for a long time. after this threshold value is reached.

2. Materials and Methods

To evaluate the technical condition of electric networks special automated systems [9-14], based on the expert evaluation method, have been developed. This technique is based on the opinion of highly qualified specialists, the experts in the field of operating electrical networks and the real technical condition of the equipment under study. However, according to the studies [9], with the widespread introduction of such systems, employees of electric grid companies conducting the corresponding evaluation have different qualifications and experience in this field. So the final assessment of the technical condition of electric grids will obviously be subjective and inaccurate. Therefore identifying unreliable equipment based on such estimates will not be possible.

The main body regulating the electric power industry in Russia, the Ministry of Energy of the Russian Federation, has expressed its interest and support for this topic. The Ministry of Energy made recommendations on the further research development direction, namely, that the technical condition of electrical equipment should be determined on the basis of technical diagnostics, statistics of defects and failures in order to assess the equipment wear level and the failures probability, what is not implemented in existing methods. Guided by this recommendation, as an indicator describing the electric grid technical condition we will take the probability of electric grid infrastructure elements failure.

As previously mentioned, in order to evaluate technical condition of the electric grid, electricity companies make control measurements of some indicators specific to the type of electrical installation under consideration [15-20]. In this regard the construction of mathematical models of electrical networks failure probabilities should be carried out on the basis of these values. This will allow to rely on the accumulated statistical base and will not require additional costs for creating new approaches to electrical equipment testing.

Electrical grids elements failure can occur due to a huge number of reasons which, in turn, leads to various options for emergency development [16-19]. However, after analyzing the essence of the physical processes leading to emergency, as well as the measured control electrical values of electrical equipment, three large groups of emergency conditions were identified:

- current-conducting elements failure;
- insulation failure;
- electric network element failure an due to mechanical damage.

Let us consider mathematical models of a separate emergency mode for each of the indicated types and simulate failure probability of live parts of the electric network elements.

3. Results

As an example, let us consider a contact of arbitrary shape, for which P_{break} is the probability of contact breaking. The contact zone has a rather complex shape (Figure 1).

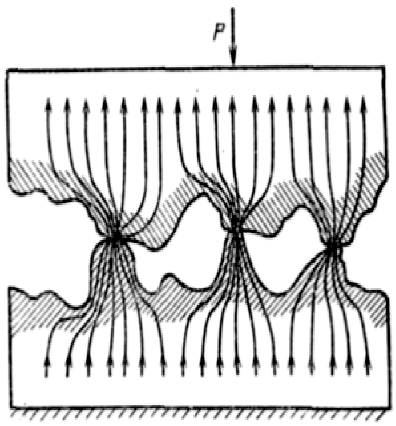

Figure 1. Contact zone form.

Let us divide the entire contact area into small areas. Then the contact break probability for the considered zone will be determined by the formula:

$$P_{break} = (1 - p_{work})^n. \tag{1}$$

As a result of dividing the contact zone into small areas, we can imagine that the total resistance (R_{cont}) will be composed of the resistances of its parts (r_{cont}) connected in parallel. In this case:

$$R_{cont} = r_{cont} / n \Rightarrow n = r_{cont} / R_{cont} . \tag{2}$$

Let us consider the failure probability of one such part contact. The probability of the area operation capability is that lower, the higher the contact resistance is [18]. The nature of such relationship is very difficult to evaluate. However, any dependence can be represented in the form of a polynomial, and, therefore, the following expression will be true:

$$P_{work} \sim \frac{1}{\left(a_0 r_{cont}^m + a_1 r_{cont}^{m-1} + \ldots + a_m r_{cont}^0\right)}, \tag{3}$$

where m is polynomial degree of the.

Let us consider the probability of contact operability for the area allocated in a certain contact zone. It will depend on a large number of factors: the material state (surface roughness, films formation, the presence of cracks and indentations), the operating conditions of the electric grid (overload, overvoltage, high currents, mechanical stress), and environmental conditions (temperature, air humidity, the presence of aggressive media), etc [21]. All these factors in one or another way affect the probability of contact breaking. And since the research is conducted for some fixed state, we have the opportunity to express this set of parameters in terms of some constant (C).

In this case the expression will be true:

$$P_{work} = \frac{\mathrm{C}}{\left(a_0 r_{cont}^m + a_1 r_{cont}^{m-1} + \ldots + a_m r_{cont}^0\right)}. \tag{4}$$

Then the probability of contact breaking will be calculated by the formula:

$$P_{\mathrm{break}} = \left(1 - \frac{\mathrm{C}}{\left(a_0 r_{cont}^m + a_1 r_{cont}^{m-1} + \ldots + a_m r_{cont}^0\right)}\right)^{\frac{r_{cont}}{R_{cont}}}. \tag{5}$$

We take out the value r_{cont}^m outside the polynomial and replace $r_{cont} = -x$, then we get:

$$P_{\mathrm{break}} = \frac{1}{\left(1 + \frac{\mathrm{C}}{x \cdot r_{cont}^{m-1}\left(\frac{a_0 r_{cont}^m + a_1 r_{cont}^{m-1} + \ldots + a_m r_{cont}^0}{r_{cont}^m}\right)}\right)^{\frac{x}{R_{cont}}}}. \tag{6}$$

As the number of partitions increases to infinity, the resistance of the part r_{cont} will tend to infinity, therefore x will also tend to infinity, and the quantity $\left(1 + \frac{1}{x}\right)^x$, when x approaches infinity, will equal the exponent «*e*» (the second special limit). Ratio limit $\frac{a_0 r_{cont}^m + a_1 r_{cont}^{m-1} + \ldots + a_m r_{cont}^0}{r_{cont}^m}$ for r_{cont} tending to infinity will be determined by the ratio of the coefficients of the polynomial highest degrees and is equal to a_0. We replace the ratio of two constants $\frac{C}{a_0} = A_{cont}$.

Thus, the expression will be true:

$$P_{\text{break}} = \frac{1}{\sqrt[R_{cont}]{e^{\frac{A_{cont}}{r_{cont}^{m-1}}}}}. \tag{7}$$

Due to the fact that the probability value should not depend on the method of the contact surface partitions, i.e. it should not depend on the method of the part discretization (how small considered parts are) and it should not depend on r_{cont} of discrete part, therefore, the value r_{cont}^{m-1} should be a constant value, and therefore $m = 1$. Then finally:

$$P_{\text{break}} = \frac{1}{\sqrt[R_{cont}]{e^{A_{cont}}}}. \tag{8}$$

Note that the derived formula will be valid not only for the contact connections failure, but also for all current conducting parts as a whole, since the nature of the physical phenomena occurring in these objects is identical.

In order to unify the symbols in the constructed mathematical models we shall indicate the contact breaking probability P_{break} as P_{cont} by this value we will generally understand the probability of current conducting parts failure including electrical contact connections.

We will transfer the contact resistance from absolute values to relative onees:

$$R_{cont} = \frac{R_{\text{cont.meas}}}{R_{\text{cont.norm}}}, \tag{9}$$

where $R_{cont.meas}$ is the value of contact resistance measured during the test of electrical equipment;

$R_{cont.norm}$ – the standard value of the contact resistance regulated by Electric Installation Code.

Then formula (8) will have the following form:

$$P_{cont} = \frac{1}{\sqrt[\frac{R_{\text{cont.meas}}}{R_{\text{cont.norm}}}]{e^{A_{cont}}}}. \tag{10}$$

In this case, the constant A_{cont} is determined as follows:

$$A_{cont} = \ln\left(\frac{1}{\omega \cdot \alpha_{cont}}\right) \cdot \frac{R_{\text{cont.meas}}}{R_{\text{cont.norm}}}, \tag{11}$$

where ω is the failure flow parameter for the considered type of electric grid equipment;
α_{cont} – the proportion of the investigated electrical equipment of a particular type with which an accident occurred due to current conducting parts failure.

The conclusion of the formula for the probability of failure (breakdown) of electric grid element insulation is similar to the conclusion made for current conducting parts. Therefore, we present a mathematical model of insulation breakdown without proof:

$$P_{insul} = \frac{1}{\sqrt[R_{\text{insul.norm}}]{e^{A_{insul}}}^{\frac{R_{\text{insul.meas}}}{}}}. \tag{12}$$

The constant A_{insul} is defined as follows:

$$A_{insul} = \ln\left(\frac{1}{\omega \cdot \alpha_{insul}}\right) \cdot \frac{R_{\text{insul.meas}}}{R_{\text{insul.norm}}}, \tag{13}$$

where α_{insul} is a statistical indicator showing the share of electrical equipment that has failed due to insulation breakdown.

Various regulatory and technical documents do not regulate the measurement of electrical equipment control parameters to determine mechanical damage. Moreover their very presence, nature and intensity can indirectly indicate a certain technical condition of the electric grid element [22-23]. Since mechanical damage cannot be formalized in the form of electrical quantities (resistance or current) it is possible and advisable to use the method of expert evaluation in this case.

In the conditions of Russian electric grids operation the experts are often operational personnel who can evaluate the technical condition of the same element in different ways or incorrectly. To reduce subjectivity and increase evaluation accuracy a rigid scale of generalized expert evaluation of electrical equipment was developed. An expert from the operating personnel clearly defines the actual state of the electrical equipment by the description given in the developed scale and sets a certain point rating corresponding to the scale. The rating scale has a gradation of 1 to 10 points, where “1” is the worst condition, “10” is the best condition.

We note that we will set three qualitative states of the electric network elements:

- “Good” is the state of the least failure probability;
- “Satisfactory” - the state when failure probability is possible;
- “Unsatisfactory” - the state with high failure probability.

On the basis of the foregoing we will compile generalized criteria and a scale for the expert evaluation of mechanical defects in power grid equipment (Table 1).

A universal algorithm was developed for the expert evaluation of mechanical defects in power grid equipment according to which the operating personnel of the power grid company should make a decision on assessing the technical condition of the considered electrical installation.

Evaluation must be carried out starting with a description of "10". Highest rating this description is a set of the element qualitative characteristics, which can be estimated at 10 points and determine the condition as the best. If the qualitative description of the element state does not match to any of the presented items it is necessary to lower the maximum rating:

- by 1 point if the element state corresponds to a similar paragraph in the description of “6” expert evaluation;
- by 2 points if the element state of corresponds to a similar item in the description of “2” expert evaluation.

After conducting expert evaluation of electrical equipment mechanical defects it is necessary to transform the result of expert evaluation into probabilistic form. In the course of research it was determined that the mathematical model of the probability of these types of damage would be:

$$P_{\text{mech.def}} = A_{mech} \cdot \frac{\sqrt[10]{10.3} - \sqrt[10]{B_{EA}}}{\sqrt[10]{10.3}}, \tag{14}$$

where $P_{mech.def}$ is the of power grid equipment failure probability due to mechanical defects (damage);
B_{EA} is an expert assessment of the electric grid company operating personnel;
A_{mech} is a coefficient taking into account the statistics of defects in electrical equipment in case of mechanical damage.

Table 1. Generalized criteria and scale of expert evaluation of mechanical defects in power grid equipment

Evaluation Scale of Electric Network Element	Qualitative Description of Electric Network Element Technical Condition Evaluation
10 “good”	1) The fastening of electrical equipment is strong and reliable without changing its position from the original; 2) The surface of the insulators is clean and smooth, has no defects (chips, cracks); 3) In the places of current conducting elements connection there are no traces of corrosion, deformation, mobility; 4) Other elements do not have chips, cracks, deformations, traces of corrosion.
6 “satisfactory”	1) The fastening of electrical equipment is dense, a slight change in position from the original one is possible due to mechanical stress; 2) The surface of the insulators has insignificant chips, cracks, discoloration of part of the surface (at least one sign); 3) At the junction of current conducting elements slight traces of corrosion are observed while there are no other defects; 4) Other elements have insignificant chips, cracks, deformations, traces of corrosion (one sign at least).
2 “unsatisfactory”	1) The fastening of electrical equipment is weak, the housing is movable; 2) The surface of the insulators has significant chips, cracks, there are traces of an electric arc (one sign at least); 3) Blackening, significant deformations are observed at the junction points of current conducting elements, there is mobility in the joints (one sign at least); 4) Other elements have significant chips, cracks, deformations, traces of corrosion (one sign at least).

The failure of electric network element will occur on the whole if at least one of the above types of emergency conditions comes fully out. In the theory of power supply reliability this situation is regarded as buck connection of electric circuit elements. Then the mathematical model of the failure probability of electric network element as a whole will have the following form:

$$P = 1 - (1 - P_{insul})\cdot(1 - P_{cont})\cdot(1 - P_{mech.def}). \tag{15}$$

4. Discussion

As an example of using this technique to evaluate technical condition of the electric network elements and on this base to select the most unreliable element for its repair let us consider two real electric network elements of the same type, for example, two disconnectors. Table 2 shows the results of control measurements of electrical parameters and expert evaluation of mechanical defects of these disconnectors.

Table 2. Information on conducting control measurements of electrical parameters and expert assessment of mechanical defects of disconnectors

Disconnector Name	Measured / estimated parameter	Parameter value
Disconnector # 1	Insulation Resistance, MΩ	4350
	DC Resistance, μOhm	115
	External defects evaluation	«5»
Disconnector # 2	Insulation resistance, MΩ	13600
	DC Resistance, μOhm	107
	External defects assessment	8

We will calculate the probability of failure for Disconnector # 1.
Breakdown probability:

$$P_{\text{insul.discon.1}} = 1 - \frac{1}{\sqrt[\frac{R_{\text{insul.discon.1}}}{R_{\text{insul.discon.norm}}}]{e^{A_{\text{insul.discon.}}}}} = 1 - \frac{1}{\sqrt[\frac{4350}{1000}]{e^{0,04846}}} = 0.01108.$$

The failure probability of current conducting parts:

$$P_{\text{cont.discon.1}} = \frac{1}{\sqrt[\frac{R_{\text{cont.discon.1}}}{R_{\text{cont.discon.norm}}}]{e^{A_{\text{cont.discon.}}}}} = \frac{1}{\sqrt[\frac{115}{175}]{e^{2,941399}}} = 0.01137.$$

The probability of failure of Disconnector # 1 due to external defects:

$$P_{\text{mech.discon.1}} = A_{mech} \frac{\sqrt[10]{10.3} - \sqrt[10]{B_{\text{def.discon.1}}}}{\sqrt[10]{10.3}} = 0.015552 \cdot \frac{\sqrt[10]{10.3} - \sqrt[10]{5}}{\sqrt[10]{10.3}} = 0.001084.$$

General probability of Disconnector # 1 failure:

$$P = 1 - (1 - P_{insul.discon.1}) \cdot (1 - P_{cont.\ discon.1}) \cdot (1 - P_{mech\ discon.1}) = 0.023384.$$

Let us make a similar calculation for Disconnector # 2.
Breakdown probability:

$$P_{\text{insul.discon.2}} = 1 - \frac{1}{\sqrt[\frac{R_{\text{insul.discon.2}}}{R_{insul.\text{discon.norm}}}]{e^{A_{\text{insul.discon}}}}} = 1 - \frac{1}{\sqrt[\frac{13600}{1000}]{e^{0,04846}}} = 0.003556.$$

The failure probability of current conducting parts:

$$P_{\text{cont.discon.2}} = \frac{1}{\sqrt[\frac{R_{\text{cont.discon.2}}}{R_{\text{cont.discon.norm}}}]{e^{A_{\text{cont.discon}}}}} = \frac{1}{\sqrt[\frac{107}{175}]{e^{2,941399}}} = 0.008142.$$

The failure probability of Disconnector # 2 due to mechanical damage:

$$P_{\text{mech.discon.2}} = A_{\text{mech.discon}} \frac{\sqrt[10]{10.3} - \sqrt[10]{B_{\text{def.discon.2}}}}{\sqrt[10]{10.3}} = 0.015552 \cdot \frac{\sqrt[10]{10.3} - \sqrt[10]{8}}{\sqrt[10]{10.3}} = 0.000388.$$

General probability of Disconnector # 2 failure:

$$P = 1 - (1 - P_{insul.discon.2}) \cdot (1 - P_{cont.\ discon.2}) \cdot (1 - P_{mech\ discon.2}) = 0.012053.$$

Comparing the values of disconnectors failure probabilities it is clear that the value is greater for Disconnector # 1. Therefore Disconnector # 1 should be repaired.

5. Conclusion

Thus, taking into account the conditions of limited financial resources of electric grid companies the methodology presented in this article allows to determine the priority of replacing dilapidated electrical equipment by failure probability value of the electric network elements, what in its turn will significantly increase the reliability of power supply to consumers and reduce the level of material losses arising from emergency situation. In addition, the developed methodology for determining failure probability of electric grids completely eliminates the critical comments of the Ministry of Energy of the Russian Federation to existing methods.

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References

[1] Brown R E and Marshall M 2000 *IEEE Transactions on Power Systems* **15** 887-92
[2] Alvehag K and Awodele K 2014 *IEEE Transactions on Power Systems* **29** 6594877
[3] Bertling L, Allan R and Eriksson R 2005 *IEEE Transactions on Power Systems* **20** 75-82
[4] Xu P, Fang H, Wang H and Su Y 2018 *Power System Technology* **42** 3024-32
[5] Huo M-L, Liu Y and Yang L 2014 *Dianli Xitong Baohu yu Kongzhi/Power System Protection and Control* **42** 100-6
[6] Selvik J T and Terje A 2011 *Reliability Engineering & System Safety* **96** 324-31
[7] Da Silva A M L, Cassula A M, Billinton R and Manso L A F 2002 *IEE Proceedings: Generation, Transmission and Distribution* **149** 1-6
[8] Jurgensen J H, Nordstrom L and Hilber P 2019 *IEEE Transactions on Power Delivery* **34** 8701475
[9] Zhang X, Yue S and Zha X 2018 *IET Generation, Transmission and Distribution* **12** 295-302
[10] Park Y M, Kim G-W and Sohn J-M 1997 *IEEE Transactions on Power Systems* **12** 363-9
[11] Lin X, Ke S, Li Z, Weng H and Han X 2010 *IEEE Transactions on Power Delivery* **25** 5446314
[12] Sun J, Qin S-Y and Song Y-H 2004 *IEEE Transactions on Power Systems* **19** 2053-9
[13] Gupta P, Lin C-T, Mehlawat M K and Grover N 2016 *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans* **46** 7287778
[14] Xu B, Yin X, Zhang Z and Li X 2018 *Power System Technology* **42** 3241-8
[15] Dehghanian P, Fotuhi-Firuzabad M, Aminifar F and Billinton R 2013 *IEEE Transactions on Power Delivery* **28** 6468146
[16] Dehghanian P, Fotuhi-Firuzabad M, Aminifar F and Billinton R 2013 *IEEE Transactions on Power Delivery* **28** 6463471
[17] Brown R E, Frimpong G and Willis H L 2004 *IEEE Transactions on Power Systems* **19** 782-87
[18] Bompard E, Huang T, Wu Y and Cremenescu M 2013 *Int. J. of Electrical Power and Energy Systems* **50** 50-64
[19] Ndawula M B, Djokic S Z and Hernando-Gil I 2019 *Energies* **12** 531
[20] Shpiganovich A N, Zatsepina V I, Shpiganovich A A and Stepanov V M 2018 *EAI Endorsed Transactions on Energy Web* **18** e10
[21] Xiang Z and Gockenbach E 2006 *IEEE Transactions on reliability* **55** 361-68
[22] Allan R and Billinton R 2000 *Proceedings of the IEEE* **88** 140-62
[23] Jiang X and Sheng G 2018 *Gaodianya Jishu/High Voltage Engineering* **44** 1041-50